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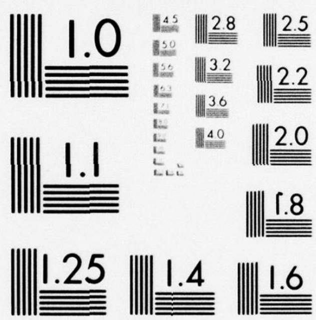

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NONDESTRUCTIVE EVALUATION PROCEDURE FOR MILITARY AIRFIELDS

by

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This report presents a procedure for the nondestructive evaluation of military airfield pavements. Nondestructive testing is performed with a 16-kip electrohydraulic vibrator, which measures the load-deflection response of pavements, and the results are reported as dynamic stiffness modulus (DSM). Correlations of the DSM to allowable single-wheel load are used with existing analytical relationships to give the allowable gross aircraft loads and required overlay thicknesses. The procedures described are based on findings from (Continued) over

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20. ABSTRACT (Continued).

earlier research studies that are referenced. Testing techniques, data reduction procedures, computational methodology, and detailed examples were developed to satisfy the need for a rapid nondestructive test procedure.

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PREFACE

The investigation reported herein was sponsored by the Office, Chief of Engineers, U. S. Army, under the Engineering Criteria for Design and Construction (O&MA) program, Project 4K07812AQ61. The study was conducted during the period 1 July 1976 - 30 September 1976.

The work was performed under the general supervision of Messrs. J. P. Sale and R. G. Ahlvin, Chief and Assistant Chief, respectively, of the Geotechnical Laboratory (GL), U. S. Army Engineer Waterways Experiment Station (WES). This report was prepared by Mr. J. W. Hall, Jr., of GL.

Director of the WES during the conduct of this project and the preparation of the report was COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
Farenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
inches	25.4	millimetres
kips (force)	4,448.222	newtons
pounds (force)	4.448222	newtons
pounds (force) per square inch	6,894.757	pascals
pounds (mass) per cubic inch	27,679.9	kilograms per cubic metre
square inches	645.16	square millimetres

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

NONDESTRUCTIVE EVALUATION PROCEDURE FOR MILITARY AIRFIELDS

PART I: BACKGROUND

Introduction

1. The use of nondestructive test procedures for pavement evaluation has been developed by the U. S. Army Engineer Waterways Experiment Station (WES) through several years of research sponsored by the Department of the Army, Department of the Air Force, and the Federal Aviation Administration (FAA). Test equipment, data collection techniques, and evaluation methodologies described herein have been developed to satisfy the need for a rapid nondestructive test (NDT) procedure for evaluation of the load-carrying capacity of pavements and have been validated through field experiments. The development of the nondestructive evaluation methodologies was basically a correlation of nondestructive pavement response data to conventional evaluation theories, which are based on direct sampling techniques. The research efforts involved in the development of the NDT evaluation procedures have been documented.[1-6]

Purpose and Scope

2. The purpose of this report is to present a procedure for the nondestructive evaluation of military airfield pavements, using nondestructive vibratory techniques. The procedure is based on results of research studies using the WES 16-kip* vibrator and correlations of the dynamic stiffness modulus (DSM) and the allowable single-wheel load (ASWL) of a pavement. Multiple-wheel effects are accounted for through use of parameters in the existing design theories, which are based on direct

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* A table of factors for converting U. S customary units of measurement to metric (SI) units is presented on page 3.

sampling techniques. The evaluation methodology given is applicable to current Army and Air Force aircraft. Predictions of allowable gross aircraft load and corresponding allowable number of operations (passes) can be made, and overlay requirements to carry projected traffic loads can be computed. An evaluation determined by the NDT methodology is based on the pavement strength condition at the time of test but does not consider fatigue effects of previously applied traffic; adjustments for previously expended traffic life and changes due to freeze-thaw or moisture levels are beyond the scope of present technology. Changes in pavement strength due to freeze-thaw cycles can be monitored with the 16-kip vibrator if desirable.

3. Because the evaluation methodology given herein is based on correlations with the 16-kip vibrator, the use of results from other vibratory devices with the methodology may produce erroneous results. However, other nondestructive devices may be used if they can be correlated to the 16-kip vibrator. The evaluation procedure should also follow the appropriate guidance given in existing pertinent technical manuals.

PART II: NONDESTRUCTIVE EQUIPMENT AND TEST PROCEDURES

Equipment

4. The evaluation procedures contained herein require the determination of the response of the pavement system to a specific steady-state vibratory loading. Inasmuch as the response of materials making up the pavement system to loading can be nonlinear, and the evaluation procedure has been developed for a specific loading system, the determination of pavement response requires a loading device that will exert a static load of 16 kips on the pavement and be capable of producing 0- to 15-kip peak vibratory loads at a frequency of 15 Hz. With the 16-kip electrohydraulic vibrator used in development of the evaluation procedure, the load is applied to the pavement surface through an 18-in.-diam steel load plate. The vibratory load is monitored by means of three load cells mounted between the actuator and the load plate, and the pavement deflection response is measured by means of velocity transducers, which are electronically integrated to produce deflection. The velocity transducers are mounted on the load plate and at points on the pavement to obtain a deflection basin measurement. Automatic data recording and processing equipment is a necessity to provide the rapid testing capability. The loading device must be readily transportable to accomplish a large number of tests in a minimum amount of time, thus avoiding interference with normal airfield operations. Figures 1 through 4, respectively, show an overall view of the WES 16-kip vibrator; a close-up of the load plate, load cells, and velocity transducers; the electronic data recording and control equipment; and a representation of the applied loading.

Data Collection

5. In the evaluation procedure, the response of the pavement system to vibratory loading is expressed in terms of the DSM. Since the time required to measure the DSM at each testing point is short (2 to 4 min), a large number of DSM measurements can be made during

the normal evaluation period. On runways and primary and high-speed taxiways, DSM tests should be made at least every 250 ft on alternate sides of the facility center line along the main gear wheel paths. For secondary taxiway systems or lesser used runways, DSM tests should be made about every 500 ft on alternate sides of the center line. For apron areas, DSM tests should be conducted in a grid pattern with spacings between 250 and 500 ft. Additional tests should be made where wide variations in DSM values are found, depending upon the desired thoroughness of the evaluation. The DSM measurements for rigid pavements should be made in the interior (near the center) of the slab. Tests for the development of the evaluation procedure were conducted at the slab centers primarily because there the results were more consistent and the correlations better. The actual layout of DSM test sites must consider the various pavement sections and construction dates. Thus, a thorough study of as-built pavement drawings is particularly helpful in designing the testing program. After the DSM tests have been performed and grouped according to pavement type and construction, a representative DSM value should be selected for computation of the allowable loading.

6. At each test site the loading equipment is positioned, and the dynamic force is varied from 0 to 15 kips (peak force) at a constant frequency of 15 Hz. The deflection of the pavement surface, measured by the velocity transducer mounted on the load plate, is plotted versus the applied load in Figure 5. The DSM (corrected, as described in paragraphs 8-11) is the inverse of the slope of the deflection versus load plot (Figure 5).

7. For rigid pavements, it is necessary to determine the deflection basin, or at least to have an additional velocity transducer positioned on the pavement at some distance (approximately 60 in.) from the load plate. As shown in Part III, the ratio of the deflection on the pavement to the deflection on the load plate determines the radius of relative stiffness, ℓ.

Data Reduction

8. The load-deflection response of pavements, particularly flexible

type, may be nonlinear at the lower force levels but becomes essentially linear at the higher force (12-15 kips). In such cases, a correction is applied to the load-deflection curve so that the DSM is obtained from the linear portion of the curve (Figure 5).

9. Changes in temperature were found to have an effect on the deflection response of asphaltic concrete (AC) pavement layers. Temperature adjustment factors for DSM measurements were developed from observations on experimental pavements (Figure 6). The mean pavement temperature may be determined directly by measuring the temperature with thermometers installed 1 in. below the top, 1 in. above the bottom, and at middepth of the AC layer and then averaging these values. An alternate method is to measure the pavement surface temperature and air temperatures and use Figure 7 to estimate the pavement mean temperature. All DSM data on flexible pavements are adjusted to a common temperature of $70^{\circ}F$ so that direct comparison can be made with data collected at varying pavement temperatures.

10. The DSM and load-carrying capacity of a pavement system can be significantly changed by the freezing and thawing of the materials, especially when frost penetrates a frost-susceptible layer of material. Correction factors to account for these conditions have not been developed. Therefore, the evaluation should be based on the normal temperature range, and if a frost evaluation is desired, the DSM should be measured during the frost-melting period.

11. A representative DSM value must be selected for each pavement group to be evaluated. Although a section of pavement may supposedly be of the same type and construction, it should be treated as more than one pavement group when the DSM values measured in one section of the pavement are greatly different from those in another section. The DSM value to be assigned to a pavement group for evaluation purposes will be the statistical mean (average) DSM for the group. Occasionally, one or two DSM values may be much higher than the other values in the group, and in such cases, the high values might be disregarded.

PART III: DEVELOPMENT OF METHODOLOGY

12. The evolvement of the nondestructive evaluation methodology is documented in previously referenced material, and only sufficient detail will be given in this report to indicate the reliability of the procedure. The methodology is based on correlations between the nondestructive DSM measurements and the computed ASWL as determined on a number of existing airport pavements representing a range of pavement types and conditions. The ASWL were computed from existing Corps of Engineers pavement design procedures, using in-place pavement strength measurements determined through test pits and direct sampling procedures.

Flexible Pavement Evaluation

13. The conventional theory used to evaluate military airfield flexible pavements is based on a determination of strength parameters, such as the California Bearing Ratio (CBR), moisture, density, classification of materials, and other values, using limitations and criteria developed from performance studies. To utilize the proven performance of the conventional methodology, the nondestructive quantity of the DSM was directly correlated to the ASWL as determined from the conventional method. Both nondestructive and direct sampling (test pits) testing were conducted on a number of in-use civil airport pavements. Figure 8 shows the results of the correlation of the DSM and the ASWL. The DSM data in Figure 8 were adjusted to a common temperature of $70^{\circ}F$ through the use of Figure 6. The correlation of Figure 8 is for a single wheel with contact area of 254 sq in. (same contact area as 18-in.-diam load plate on vibrator) and 24,000 passes (4633 coverages) of the load. Additional correlations were found for different contact areas and coverage levels. The load factor F_K (from Figure 8, F_K is 0.0437, which is obtained from the best-fit equation) from the correlations was then used to produce the relationship with the total number of coverages, as shown in Figure 9. The effect of multiple-wheel aircraft was accounted for through relationships of an equivalent single-wheel load (ESWL) to the

allowable aircraft gear load. The ESWL expressed as a percentage is shown as a function of depth in Figure 10. The thickness of the total pavement section above the subgrade is used in selection of the percent ESWL. The percent ESWL for a single-wheel aircraft is 100 percent. Table 1 presents the contact areas (A), number of main gear wheels (Nm), number of controlling wheels (Nc) used in the percent ESWL, and pass per coverage ratios for four classes of aircraft for which Army airfield evaluations are to be made. The critical aircraft in each class is also denoted in Table 1. The computation of allowable gross aircraft load P_G for a given number of coverages is determined from

$$P_G = \frac{F_k(DSM)}{S(\%ESWL)} \times \frac{Nm}{Nc} \times 100$$

where

F_k = load factor from Figure 9

S = factor that accounts for load carried by nose gear; 0.94 for C5A and 0.90 for all other aircraft

When it is desired to determine the allowable number of coverages for a specified gross load, the above equation is solved for the factor F_K. Then, Figure 9 is used to compute the allowable number of coverages. The passes are determined by multiplying the coverages by appropriate pass per coverage ratios.

14. Differences in pavement layer thicknesses and types of composition of the AC surface layer, the base course layer, and the subbase layer were equated for the correlation analysis through the use of equivalency factors. The following example illustrates the use of the equivalency factors.

15. Convert the existing pavement section to an equivalent pavement section made up of 3-in. AC, 6-in. crushed stone base, and granular subbase. Appropriate equivalency factors are selected from Table 2, and all the existing pavement is first converted to total equivalent subbase as shown in the example below. The total equivalent subbase T_s is then converted to the total equivalent pavement section T_T for evaluation.

Example of Equivalent Section

Existing Pavement	Equivalency Factor	Total Equivalent Subbase
6-in. AC	1.70	10.2
10-in. cement stabilized sand gravel base	1.60	16.0
10-in. granular subbase	1.00	10.0
		$T_s = 36.2$

The total equivalent pavement thickness for evaluation purposes is then computed as follows:

$$\begin{aligned} T_T &= 3\text{ AC} + 6\text{ base} + (T_s - 13.5)\text{ subbase} \\ &= 9 + (T_s - 13.5) \\ &= T_s - 4.5 \\ &= 36.2 - 4.5 \\ &= 31.7\text{ in.} \end{aligned}$$

Note that the 13.5 in. above is the result of converting the required 3-in. AC (equivalency factor 1.7) and 6-in. crushed stone base (equivalency factor 1.4) to equivalent subbase. If T_T is less than 13.5 in., then the equation for computing T_T is

$$T_T = 3 + \frac{T_s - 5.1}{1.40}$$

Application of the nondestructive evaluation procedure should make use of the equivalency factors for determination of the equivalent thickness in selection of the percent ESWL values.

Rigid Pavement Evaluation

16. The evaluation methodology for rigid or portland cement concrete (PCC) pavements was developed in a manner similar to the flexible pavement methodology. A correlation between the DSM and the ASWL was established from test results on 28 different pavements. The ASWL was determined with conventional evaluation criteria, using material properties (thickness, subgrade modulus, and flexural strength) measured during

direct sampling. Figure 11 shows the results of the DSM-ASWL correlation for a 254-sq-in. contact area and 24,000 passes.

17. To determine the allowable loading for aircraft having gears with different geometries, relationships between the loads of these aircraft and a single-wheel load with contact area of 254 sq in. were developed. These relationships are based upon the equivalency of maximum bending stress in the concrete slab. The radius of relative stiffness ℓ is used to interrelate the 254-sq-in. wheel to the wheel loads of different geometries through a factor F_L , as shown in Figures 12 through 15. This factor F_L is simply a ratio of the allowable gross aircraft load to the allowable load on a 254-sq-in. single wheel.

18. The radius of relative stiffness ℓ of a rigid pavement is obtainable through deflection basin measurements.[7] Figure 16 shows a correlation between ℓ determined from nondestructive deflection basin data and ℓ determined from the formula

$$\ell = \sqrt[4]{\frac{Eh^3}{12(1 - \nu^2)k}}$$

where

E = modulus of elasticity of concrete, psi (assumed to be 4×10^6 psi)

h = thickness of concrete slab, in.

ν = Poisson's ratio (assumed to be 0.2)

k = subgrade modulus from plate bearing test

Figure 17 gives the relationship between a ratio of deflections measured at points 18 and 60 in. from the center of the load plate as a function of ℓ .

19. The effects of stress repetition levels (aircraft passes) on the allowable gross aircraft load are considered by the use of traffic factors (Figures 18 and 19). The traffic factors are a function of the aircraft gear geometry, the lateral distribution of aircraft traffic on the pavement being evaluated, and the traffic volume and are independent of the pavement structure.

20. The allowable gross aircraft load P_G for a specified number

of aircraft passes is computed from the equation

$$P_G = 0.0189(DSM)(F_L)(T_c)$$

where

F_L = load factor selected from Figures 12 through 15

T_c = traffic factor selected from Figures 18 and 19

21. When it is desired to determine the allowable number of passes for a specified gross load, the above equation is solved for the factor T_c . Then, Figures 18 or 19 are entered with the value of T_c to determine the allowable number of passes for the desired aircraft.

Composite (Flexible Over Rigid) Pavement Evaluation

22. Although a procedure for evaluation of composite pavements was not developed in the referenced research reports, recent test data have resulted in such procedure. Pavement consisting of PCC slabs overlain with different thicknesses of flexible pavement (AC or AC and base course) was tested with the 16-kip vibrator along with plate bearing tests performed in test pits at the NDT locations. The composite pavements were converted to an equivalent PCC slab by the formula

$$h_e = \frac{1}{F}(h + 0.4t)$$

where

h_e = equivalent thickness of PCC

F = factor which projects the cracking that may be expected in existing PCC pavement as determined from Figure 20

h = thickness of existing PCC slab

t = thickness of AC overlay

23. The allowable load for the equivalent slab was determined by the measured values of modulus of soil reaction k , flexural strength, and equivalent slab thickness. The allowable loads for different pavement sections were correlated to the measured DSM values, as shown in

Figure 21. This correlation or the best-fit line is nearly identical to that for plain PCC pavement (Figure 11). This obviously indicates that the equivalent slab approach to composite pavements is reasonable. The DSM tests were adjusted for temperature effects in the AC overlay through the use of Figure 6.

24. The procedure for evaluation of composite pavements is to convert AC overlay and PCC slab to an equivalent thickness of PCC and use the procedure given for plain rigid pavement substituting the following equation for the allowable gross aircraft load $P_G = 0.0172(DSM)(F_L)(T_C)$. Also, the radius of relative stiffness ℓ for composite pavement cannot be determined from deflection basin measurements. The subgrade modulus k can be estimated from the subgrade soil classification and Figure 22. Then ℓ can be computed, as follows:

$$\ell = 24.4 \sqrt[4]{\frac{h_e^3}{k}}$$

where h_e represents equivalent thickness of PCC obtained from above formula. This formula for ℓ is for PCC with a modulus of elasticity of 4×10^6 psi and Poisson's ratio of 0.2.

Flexible Overlay for Flexible Pavement

25. The thickness requirements for AC overlays over flexible pavement can be determined from the NDT data. The overlay procedures use the correlations that were developed for the evaluation methodology and the relationships taken from the conventional design procedure. The allowable gross aircraft load for a single-wheel gear (P_{ASWL}) for 24,000 passes is determined for the existing pavement.

$$P_{ASWL} = \frac{F_k(DSM)}{S(\%ESWL)} \times \frac{Nm}{Nc} \times 100$$

$$= \frac{0.0437\ DSM}{0.9(100)} \times \frac{2}{1} \times 100$$

$$= 0.097\ (DSM)$$

The total equivalent pavement thickness T_T is computed as described in paragraph 15. Figures 23 through 31 (which are similar to pavement design curves) are used to obtain the required overlay thickness. Figure 23 is entered with T_T and P_{ASWL} for 24,000 passes, and the effective subgrade CBR is determined from the curve. This subgrade CBR is then used in Figures 23 through 31 with the design aircraft load and desired number of passes to determine the required total pavement thickness T_R. The difference between T_R and T_T divided by the equivalency factor for AC yields the overlay thickness. The overlay thickness t is

$$t = \frac{T_R - T_T}{1.7}$$

Overlay for Rigid and Composite Pavement

26. In order to determine overlay requirements for rigid and composite pavements, the required thickness of total concrete (PCC) to support the design load is needed. The ASWL for 24,000 passes, the subgrade modulus k, and the thickness of the existing PCC pavement (use equivalent PCC slab thickness h for composite pavements) are used with Figure 32 to obtain the flexural strength of the PCC. Then k may be obtained from the formula

$$k = \frac{(24.4)^4 h^3}{\ell^4}$$

or can be estimated from the subgrade soil classification and Figure 22. The above formula is for the conditions where the modulus of elasticity of the PCC is 4×10^6 psi and Poisson's ratio is 0.2.

27. The flexural strength is then used with Figures 32 through 54 with the subgrade modulus k, thickness of PCC, the design aircraft gross load, and the desired number of passes to obtain the required thickness h_d of PCC to support the design load. This design thickness of PCC is then converted to required overlay thickness as described in the following sections.

Flexible (AC) overlay

28. The thickness design for AC overlay over rigid or composite pavement is obtained from the formula

$$t = 2.5(Fh_d - C_b h)$$

where C_b is the condition factor for base pavement ranging from 1.0 to 0.75. For composite pavements, the existing overlay thickness is substracted from the overlay thickness t to give the required additional overlay.

Rigid overlay

29. A rigid overlay may be placed directly on an existing rigid pavement, or a leveling or bond-breaking course may be used beneath the rigid overlay. The formula that applies for the case where the overlay is placed directly on the existing rigid pavement surface is

$$h_o = \sqrt[1.4]{(h_d)^{1.4} - C_r(h)^{1.4}}$$

where

h_o = thickness of PCC overlay

C_r = condition factor of existing PCC pavement:

C_r = 1.00 (existing pavement in good condition)
C_r = 0.75 (existing pavement with initial cracks)
C_r = 0.35 (existing pavement badly cracked)

For overlay design for composite pavements or for conditions in which a leveling or bond-breaking course between the overlay and the existing PCC is necessary, the thickness of rigid overlay is obtained from

$$h_o = \sqrt{(h_d)^2 - C_r(h)^2}$$

PART IV: CONCLUSIONS AND RECOMMENDATIONS

30. This report presents procedures for the nondestructive evaluation and overlay design of military airfield pavements. The procedures are basically correlations of nondestructive vibratory test results to conventional pavement evaluation criteria. Although this report is directed primarily at aircraft operating on Army airfield pavements, the procedures are applicable to any type aircraft. Certain limitations or restrictions are inherent in the procedures. The testing must be performed with the 16-kip vibrator or a device that could produce equivalent results; the test to measure the DSM must be made at a frequency of 15 Hz with an 18-in.-diam contact load plate. Also, the thickness of the pavement layers above the subgrade and the classification of the material comprising each layer must be known. The advantages, however, of the method of evaluation are the rapid, nondestructive capability that provides minimal interference with aircraft operations. Since each test requires only a short period (about 3 min per test), a much more thorough investigation of pavement strength variability can be made than was previously possible. A higher degree of confidence in the evaluation results can be obtained because of the greater amount of pavement data.

31. The basic recommendation of this study is that the nondestructive pavement evaluation procedures should be adopted for use on military airfields. Initial stages of implementation might make use of a limited amount of test pit or core hole testing to supplement the NDT to provide confidence in the method and assure its acceptance.

32. The area in which future research efforts should be directed is the testing equipment. The vibrator size, test frequency, and other equipment characteristics need to be analyzed through experimental tests and analytical comparisons in order to optimize the equipment requirements. Also, the limitations and suitability of other commercially available NDT devices need to be investigated.

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Table 1

Aircraft Tire Contact Areas and Total Number of Main Gear Wheels

Aircraft Class	Aircraft	Tire Contact Area, sq in.	Total No. of Main Gear Wheels, N_m	No. of Controlling Wheels, N_c	Pass per Coverage Ratio* Taxiways and Runway Ends	Pass per Coverage Ratio* Runway Interior
I	OV-1*	70	2	1	10.24	15.77
	H-34		2			
	YAO-1		2			
	H-21		2			
II	CH-54 A/B**	106	4	2	4.31	8.51
	CH-47 A/B	44.5	4			
	CH-37		4			
III	C-130**	400	4	2	2.09	4.05
	C-47	256	2		5.2	
	C-123	272	2		5.23	10.38
	C-119	226	4			
	C-54	226	4			
	C-118	226	4			
	C-131	152	4			
IV	C-124**	630	4	2	2.19	3.77
	C-133	400	8			
	C-141**	208	8	4	1.72	3.17
	C-5A	285	24	24	0.81	1.10

* Pass per coverage ratios for flexible pavement.

** Indicates critical aircraft of each class for which evaluations are generally made.

Table 2

Equivalency Factors

Material	Stabilizing Agent	Surface Course	Base Course	Subbase Course	Subgrade
Asphaltic concrete	Asphalt	1.70	1.70	1.70	--
Unbound crushed stone	--	--	1.40	1.40	--
Sand-gravel	Cement	--	1.60*	1.60**	--
Clay-gravel	Cement	--	1.45*	1.45**	--
Fine-grained soil	Cement	--	1.25*	1.25**	--
Clay-sand	Cement	--	1.15*	1.15**	--
Clay-sand	Fly ash	--	--	1.15**	--
Sand-gravel or clay-gravel†	Asphalt	--	1.50	1.50	--
Fine-grained soil	Lime	--	--	1.10††	1.10‡
Unbound granular material	--	--	--	1.00	--

* To use equivalency factor in evaluation, unconfined compressive strength of layer must be 1000 psi.

** To use equivalency factor in evaluation, unconfined compressive strength of layer must be 700 psi.

† Bituminous.

†† To use equivalency factor in evaluation, unconfined compressive strength of layer must be 2000 psi.

‡ To use equivalency factor in evaluation, unconfined compressive strength of layer must be 100 psi.

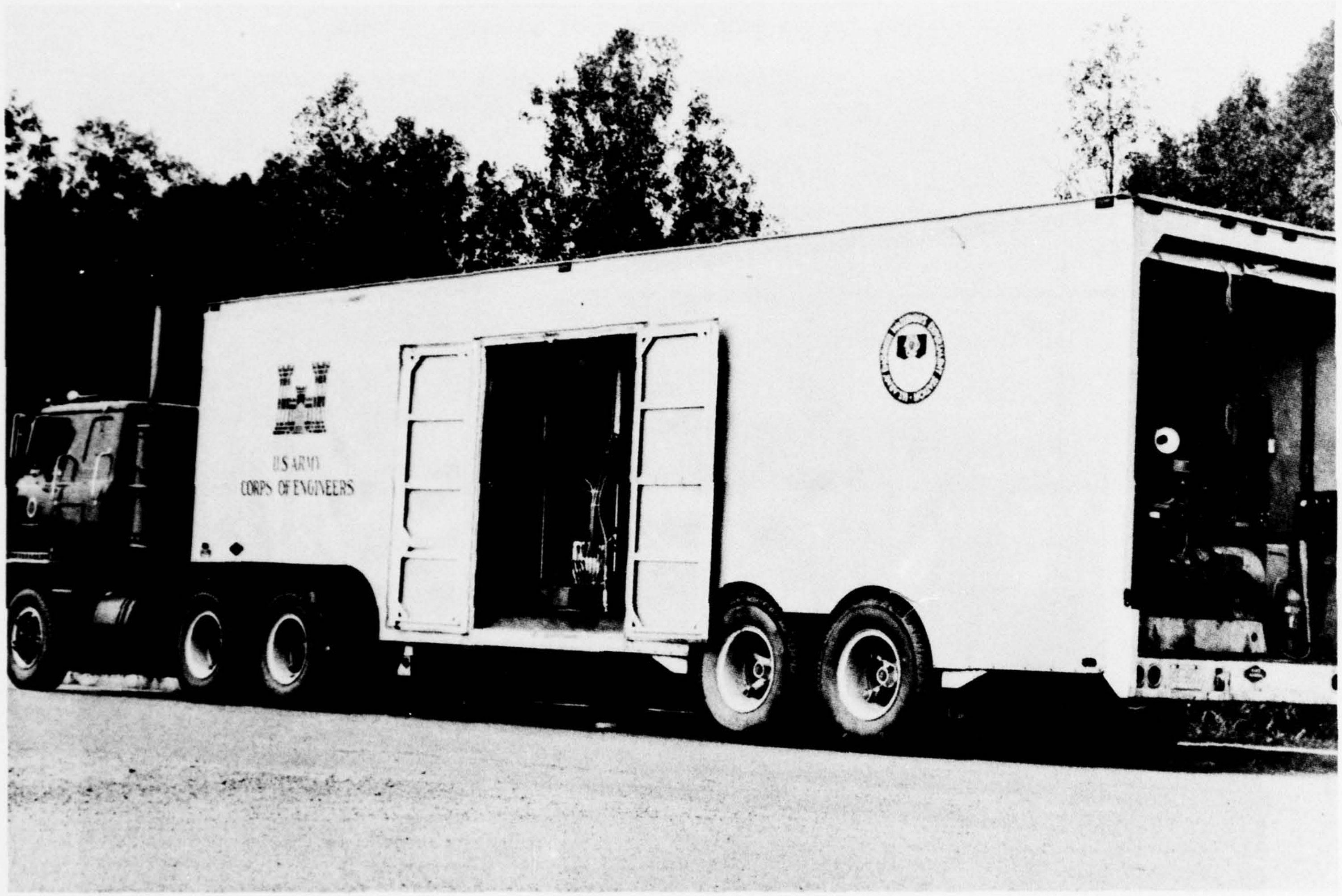

Figure 1. The WES 16-kip vibrator

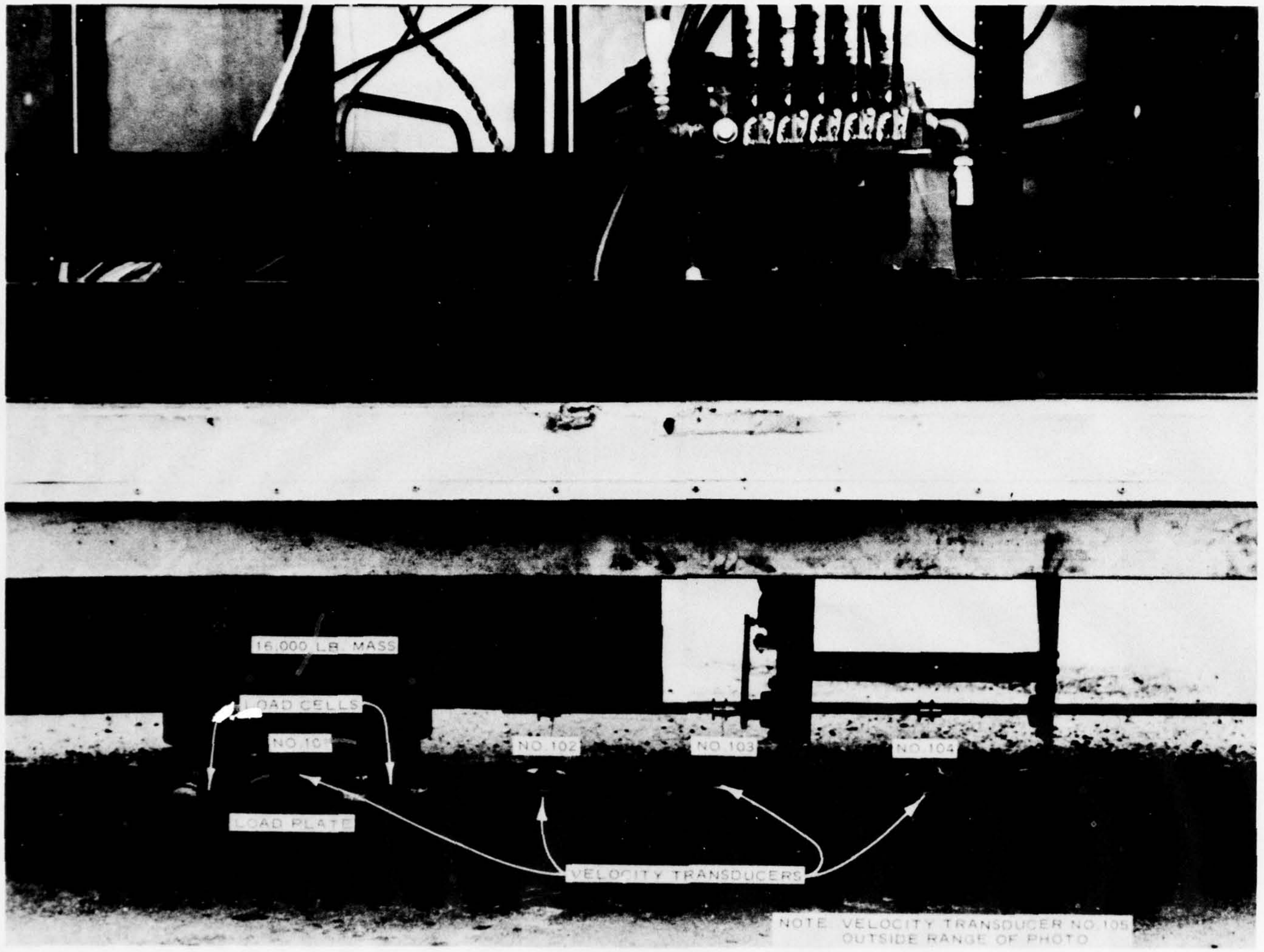

Figure 2. View of load plate, load cells, and velocity transducers of the 16-kip vibrator

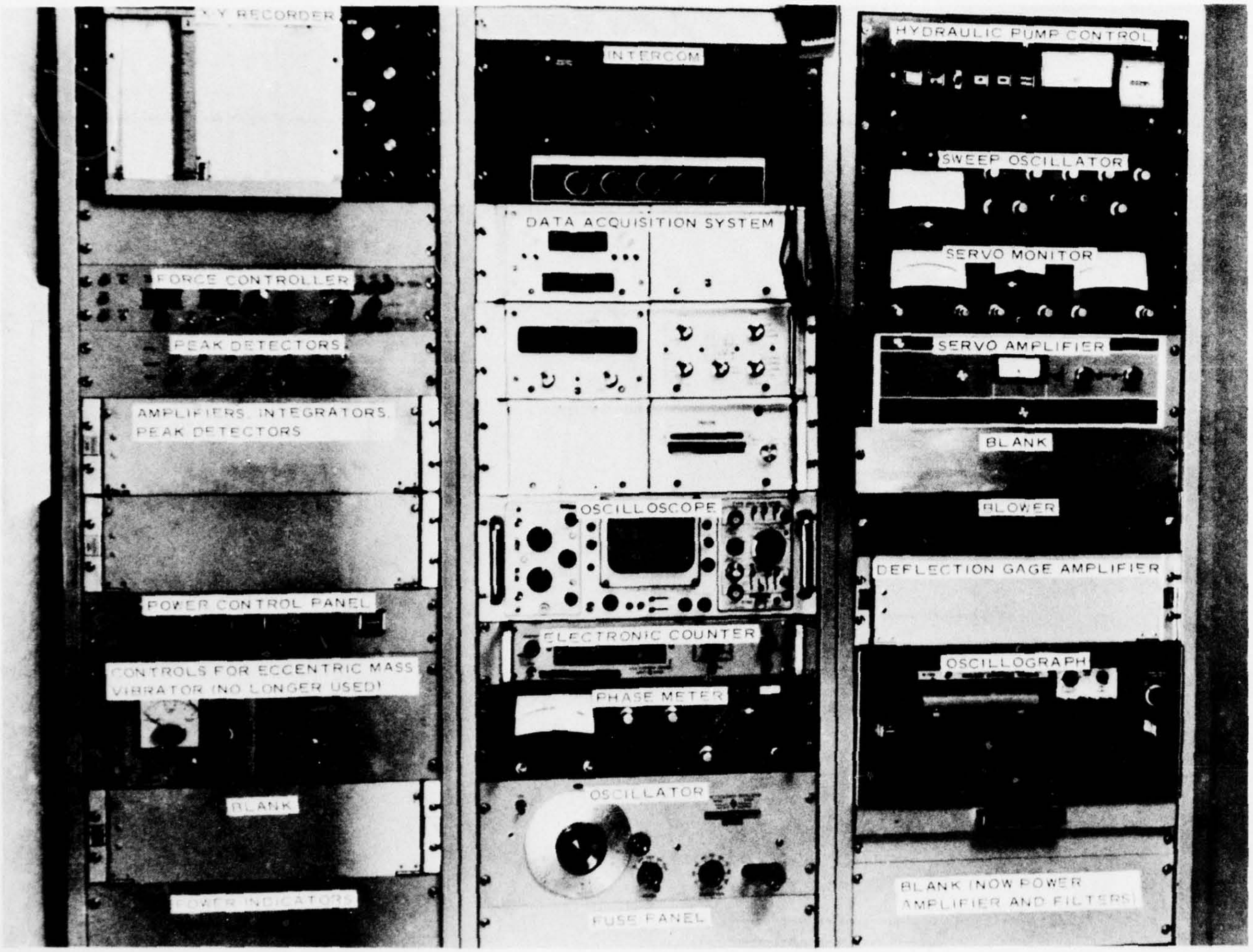

Figure 3. Electronic equipment in the 16-kip vibrator

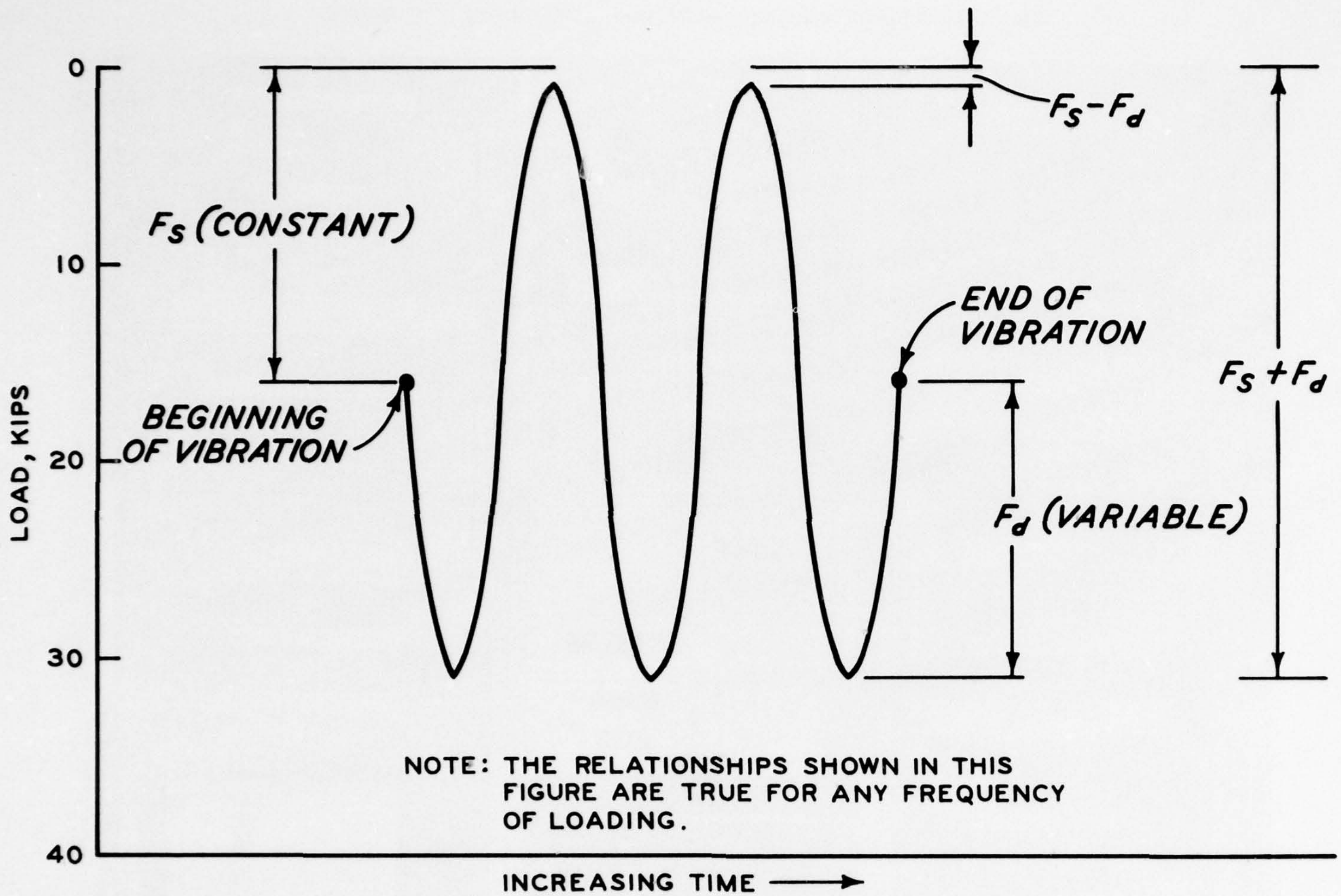

Figure 4. Load versus time relationships for loading conditions beneath the 16-kip vibrator

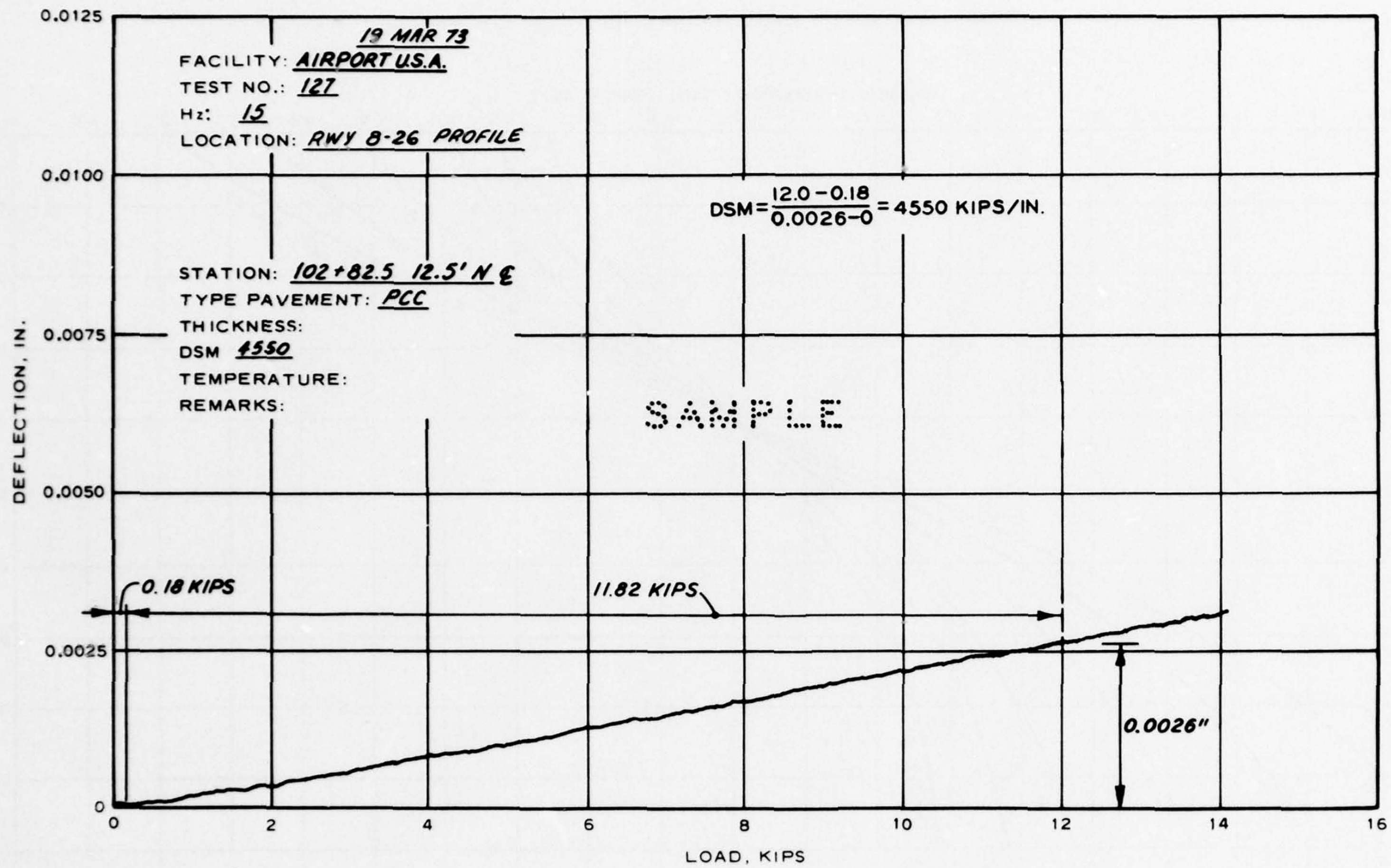

Figure 5. Deflection versus load

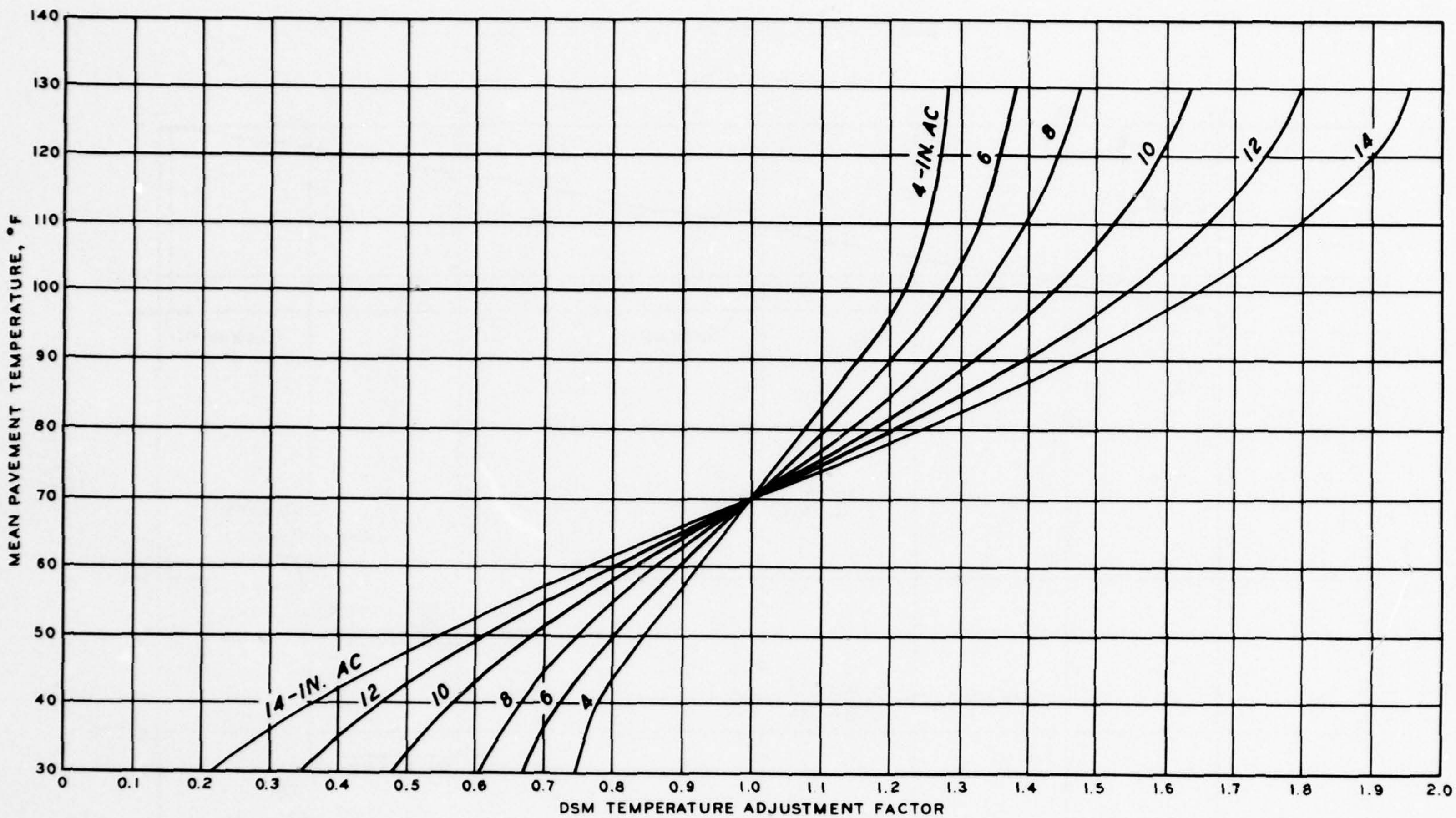

Figure 6. The DSM temperature adjustment curves

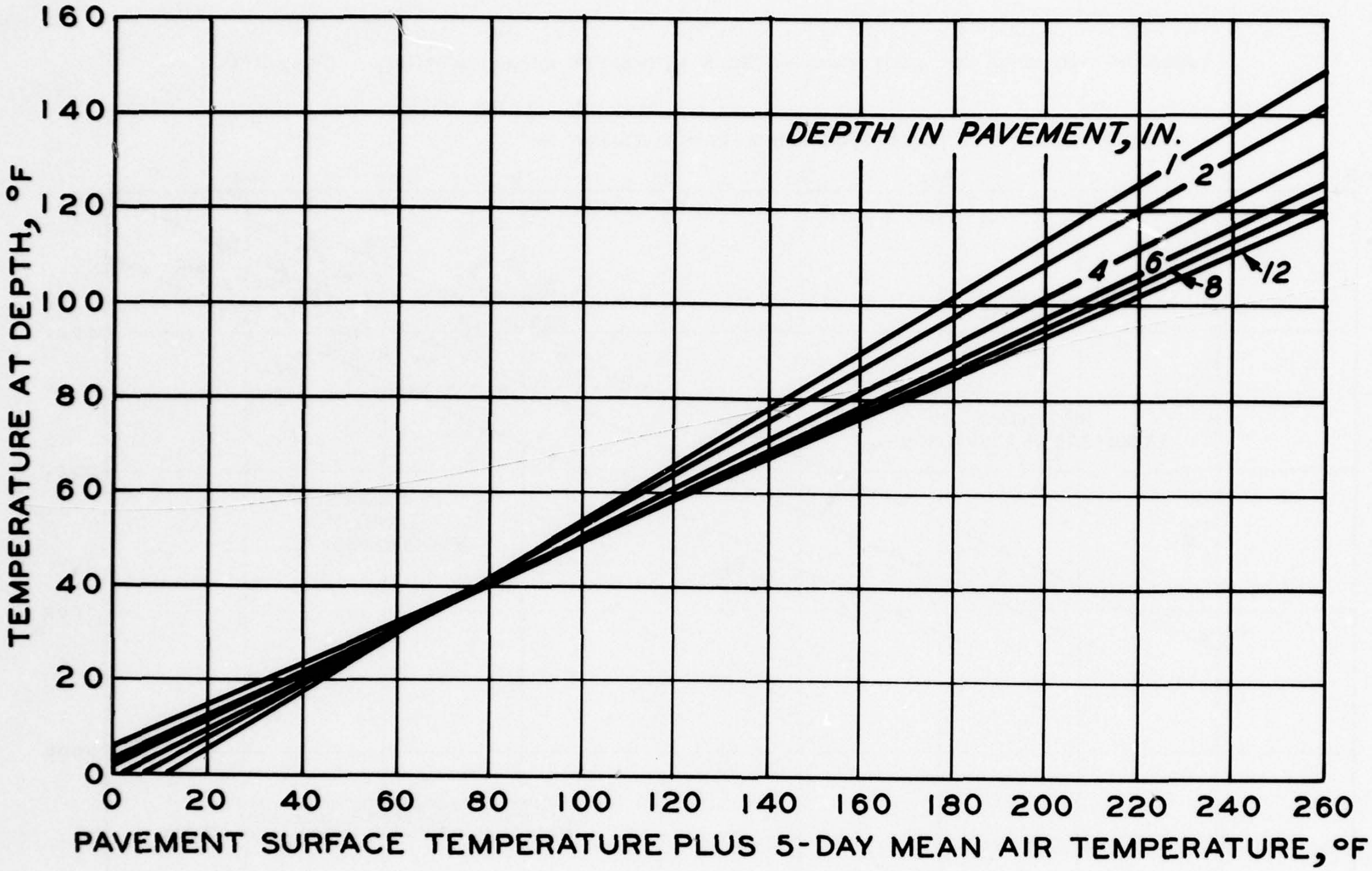

Figure 7. Prediction of pavement temperatures for bituminous layers

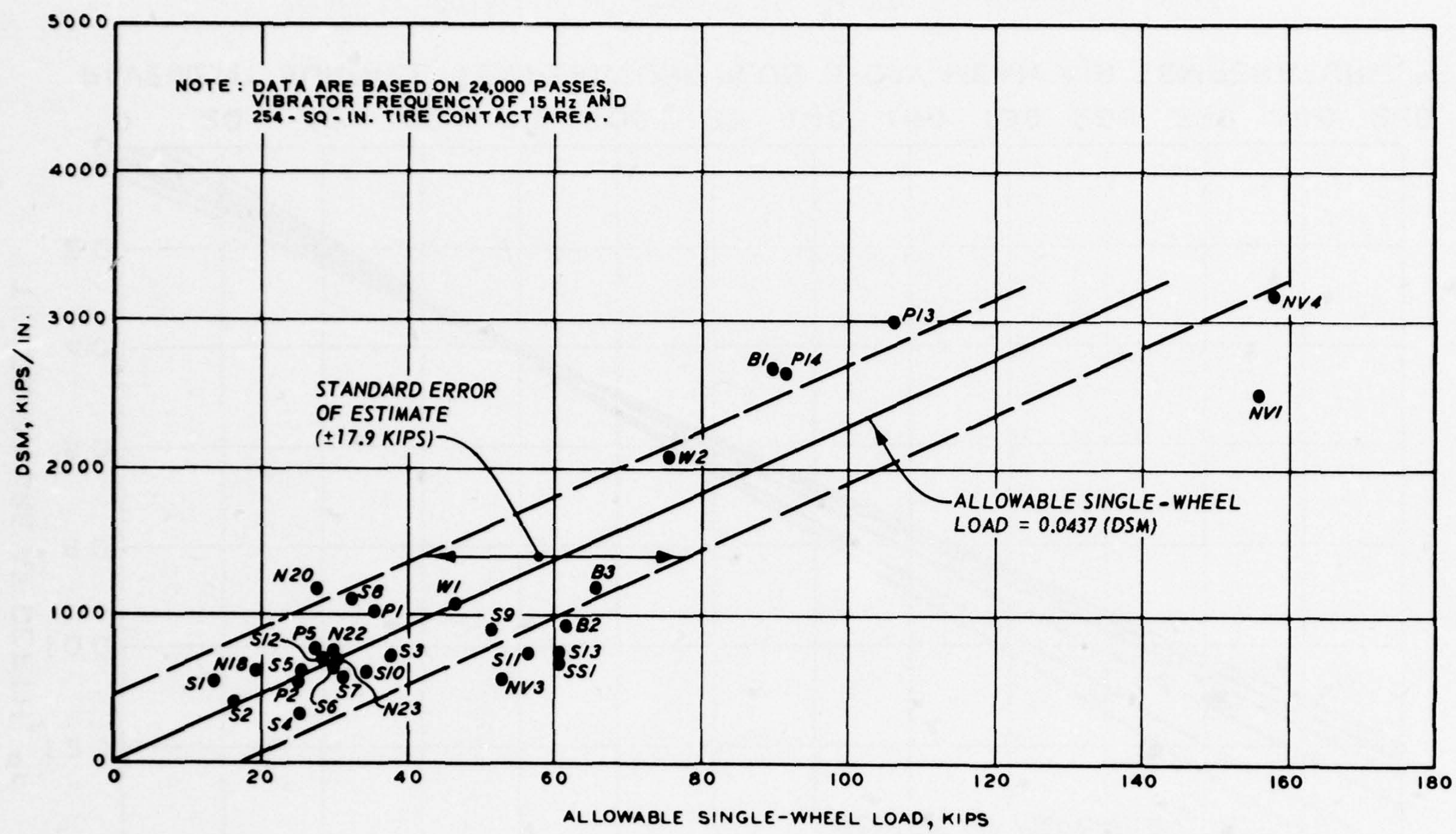

Figure 8. The DSM versus allowable single-wheel load for flexible pavement

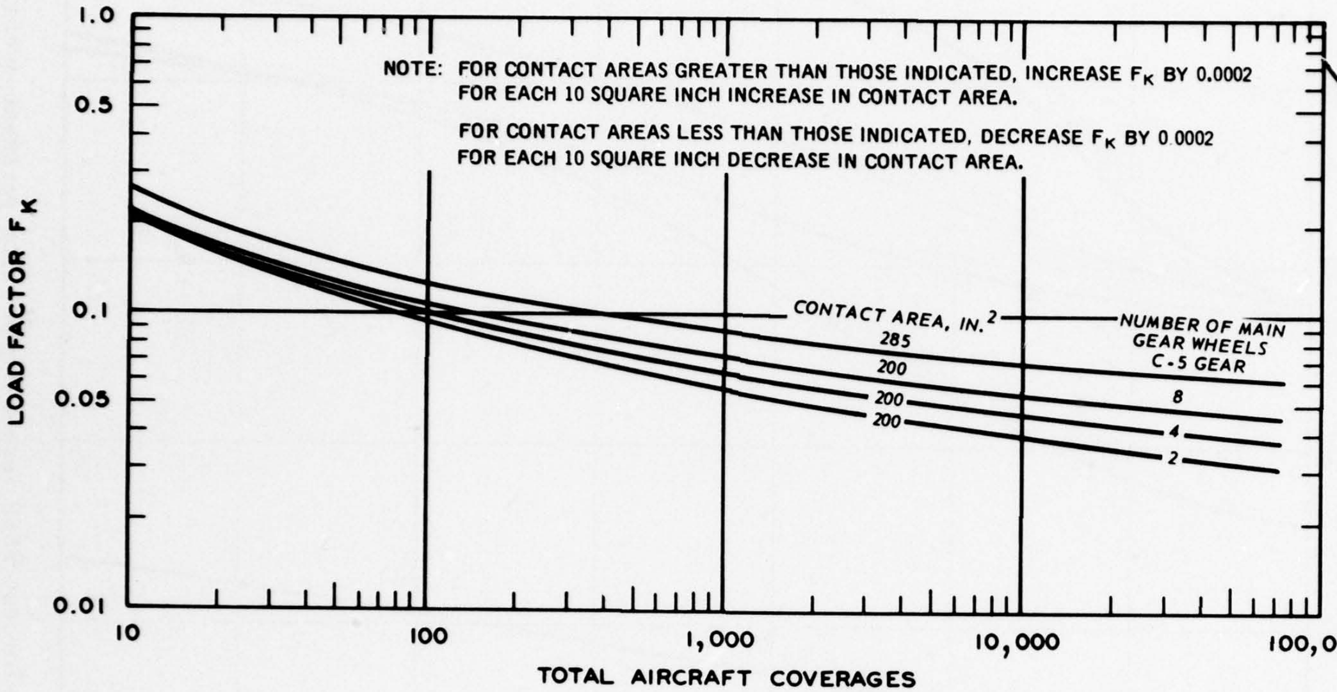

Figure 9. Load factor versus aircraft coverages

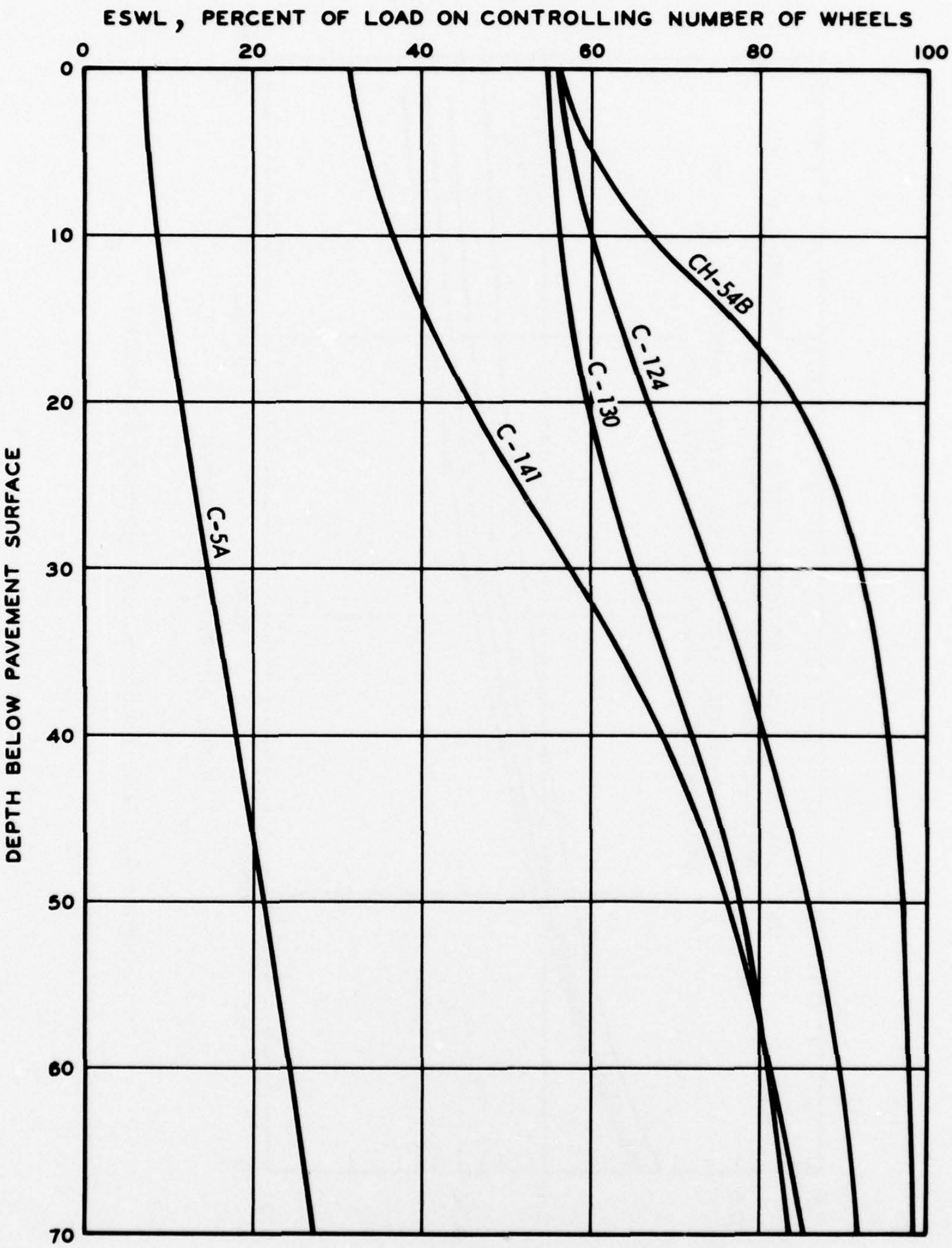

Figure 10. Percent ESWL versus depth below pavement surface

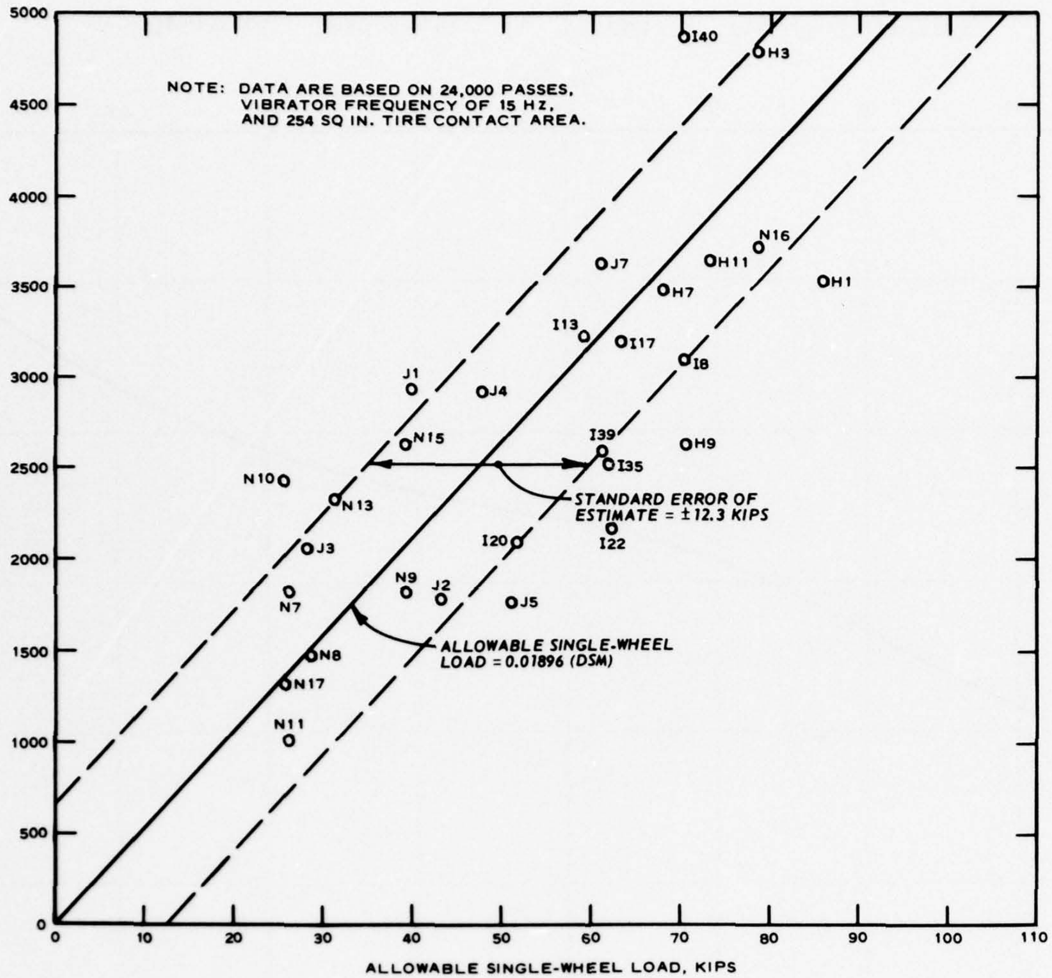

Figure 11. The DSM versus allowable single-wheel load on rigid pavement

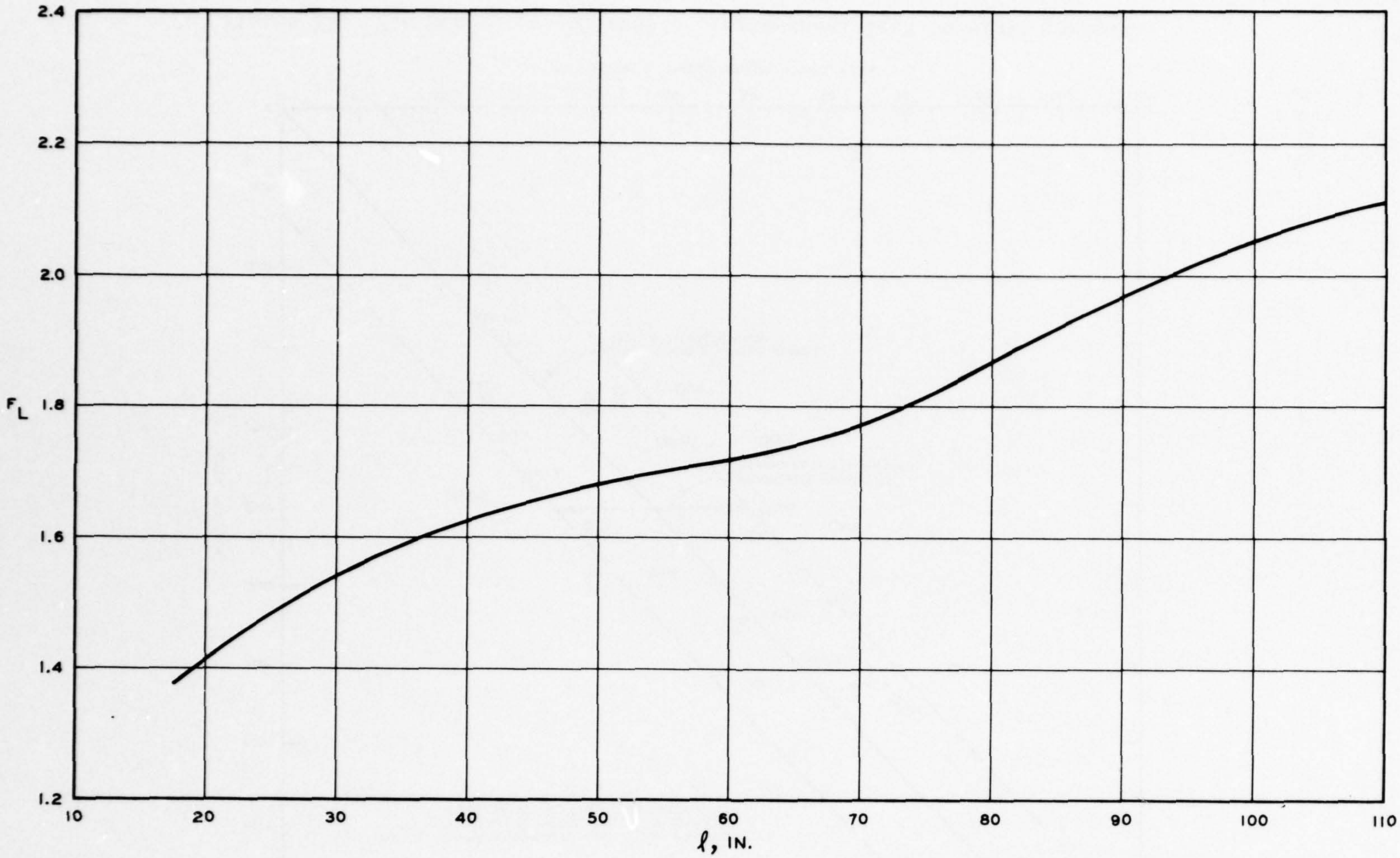

Figure 12. Load factor F_L versus ℓ for OV-1 aircraft

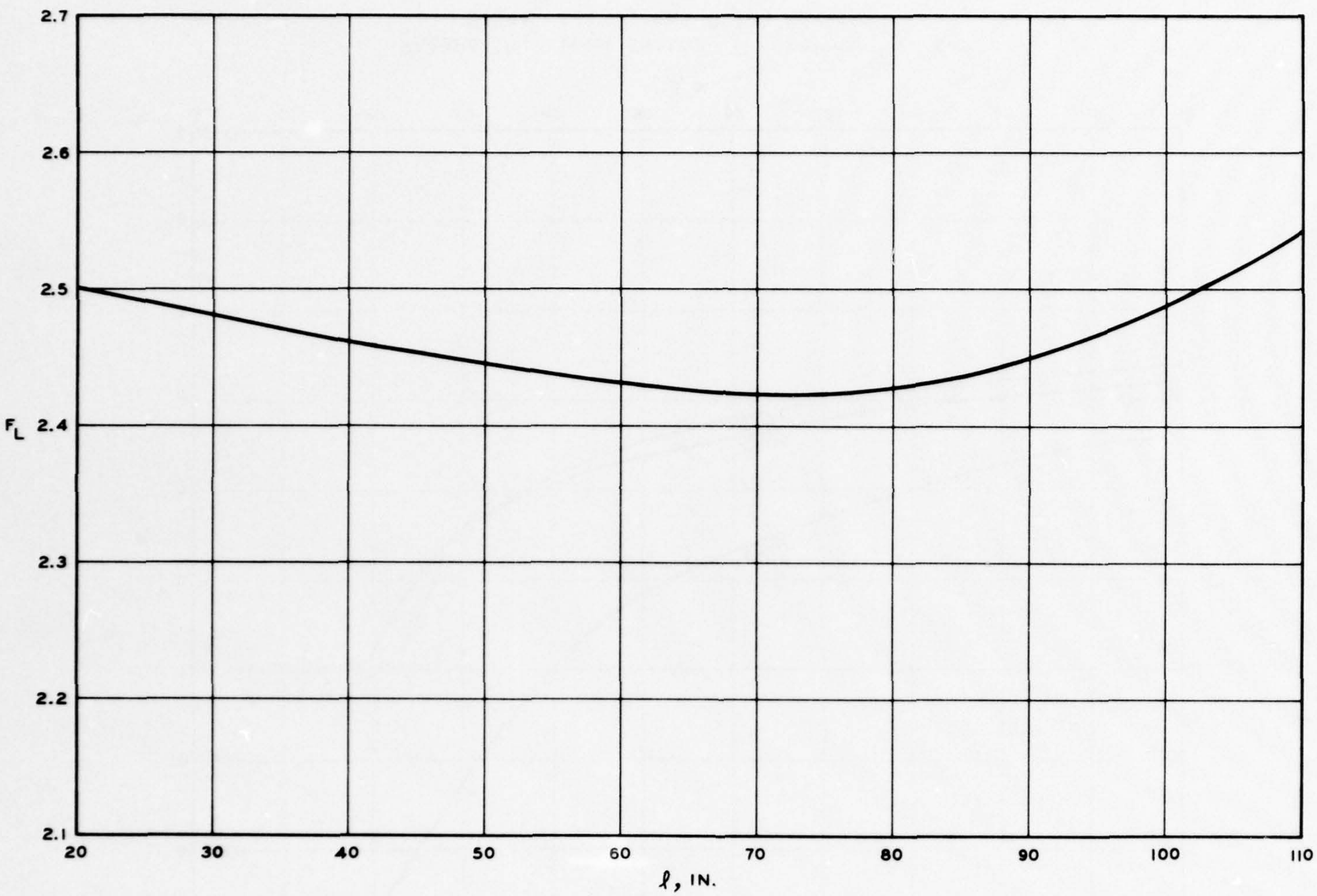

Figure 13. Load factor F_L versus ℓ for CH-54 aircraft

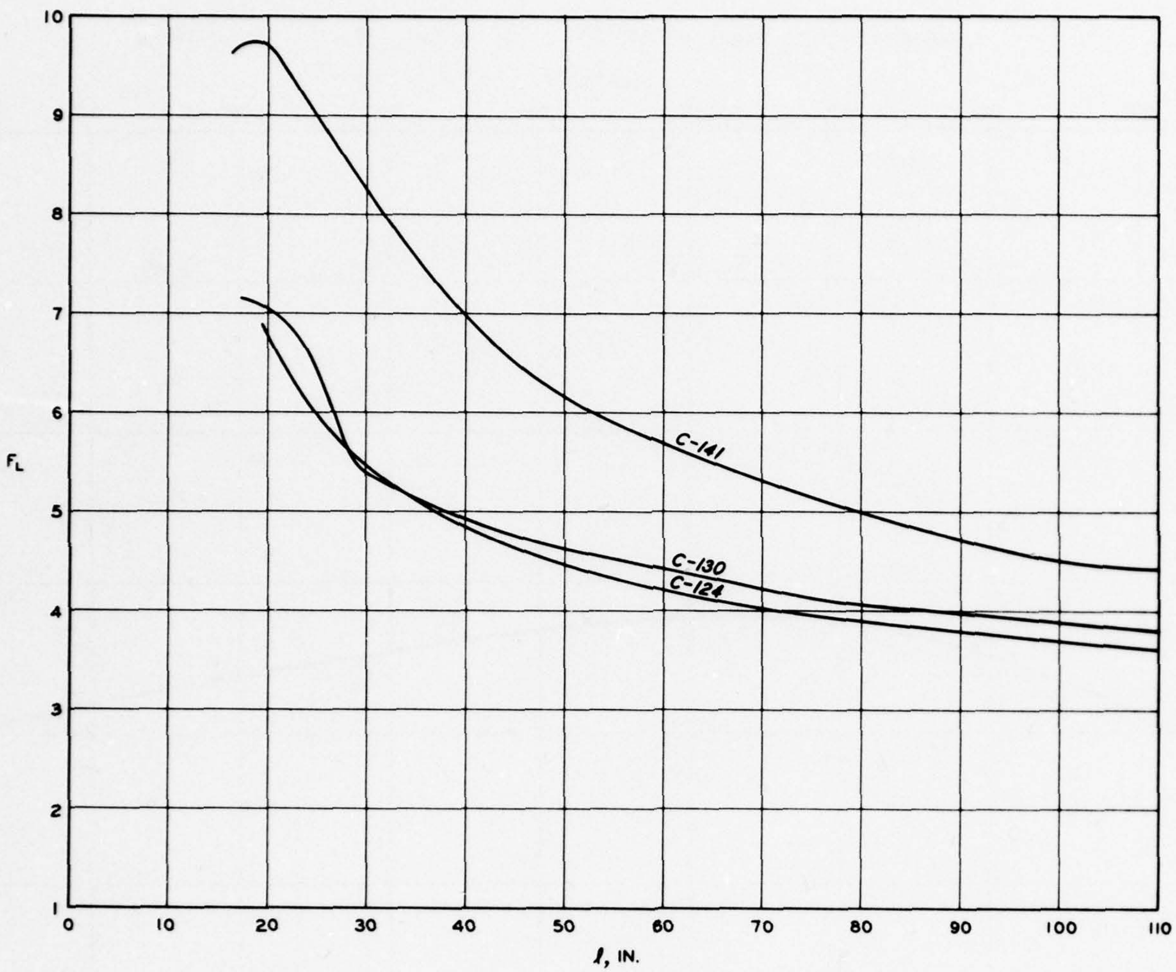

Figure 14. Load factor F_L versus ℓ for C-141, C-130, and C-124 aircraft

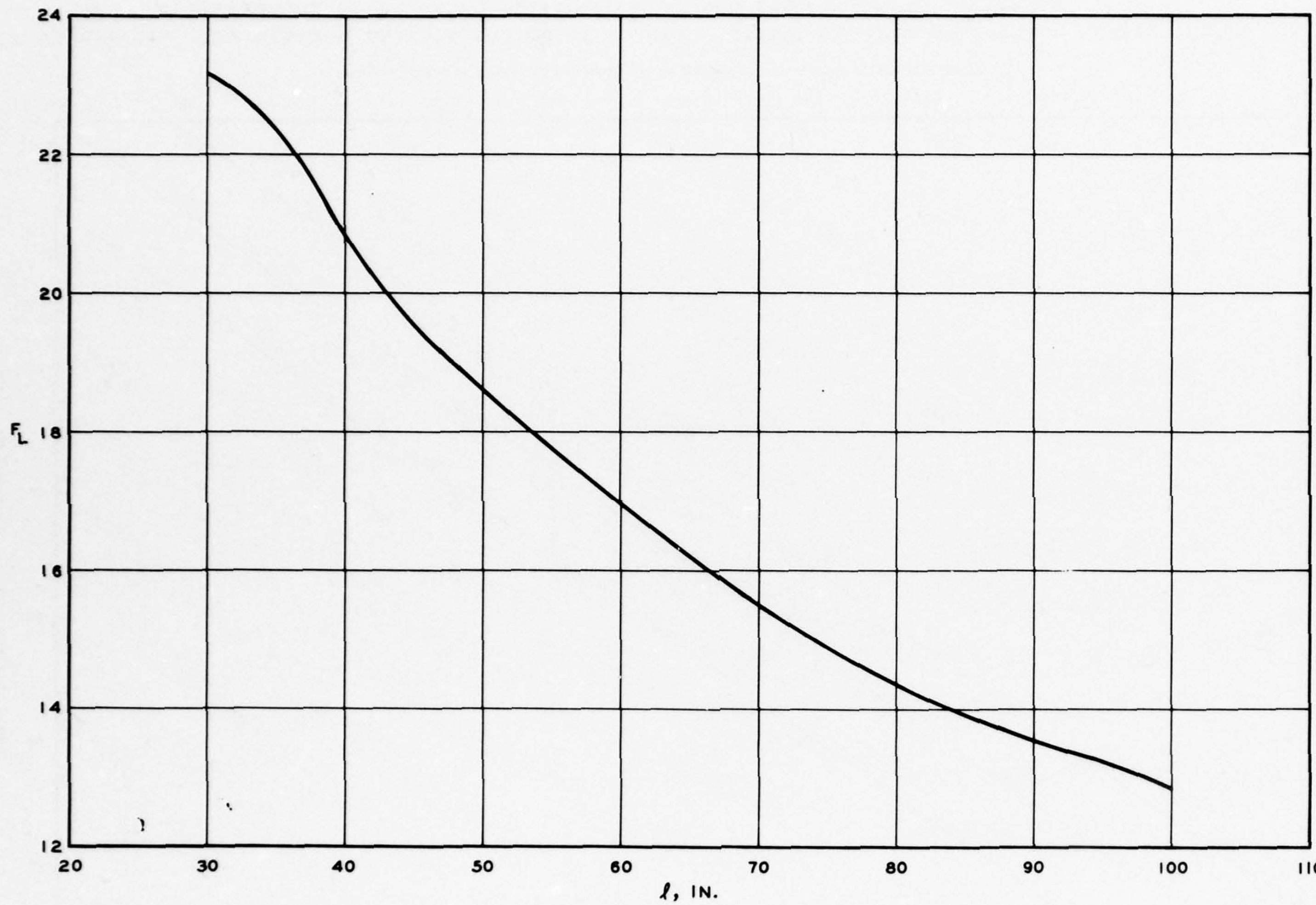

Figure 15. Load factor F_L versus ℓ for C-5A aircraft

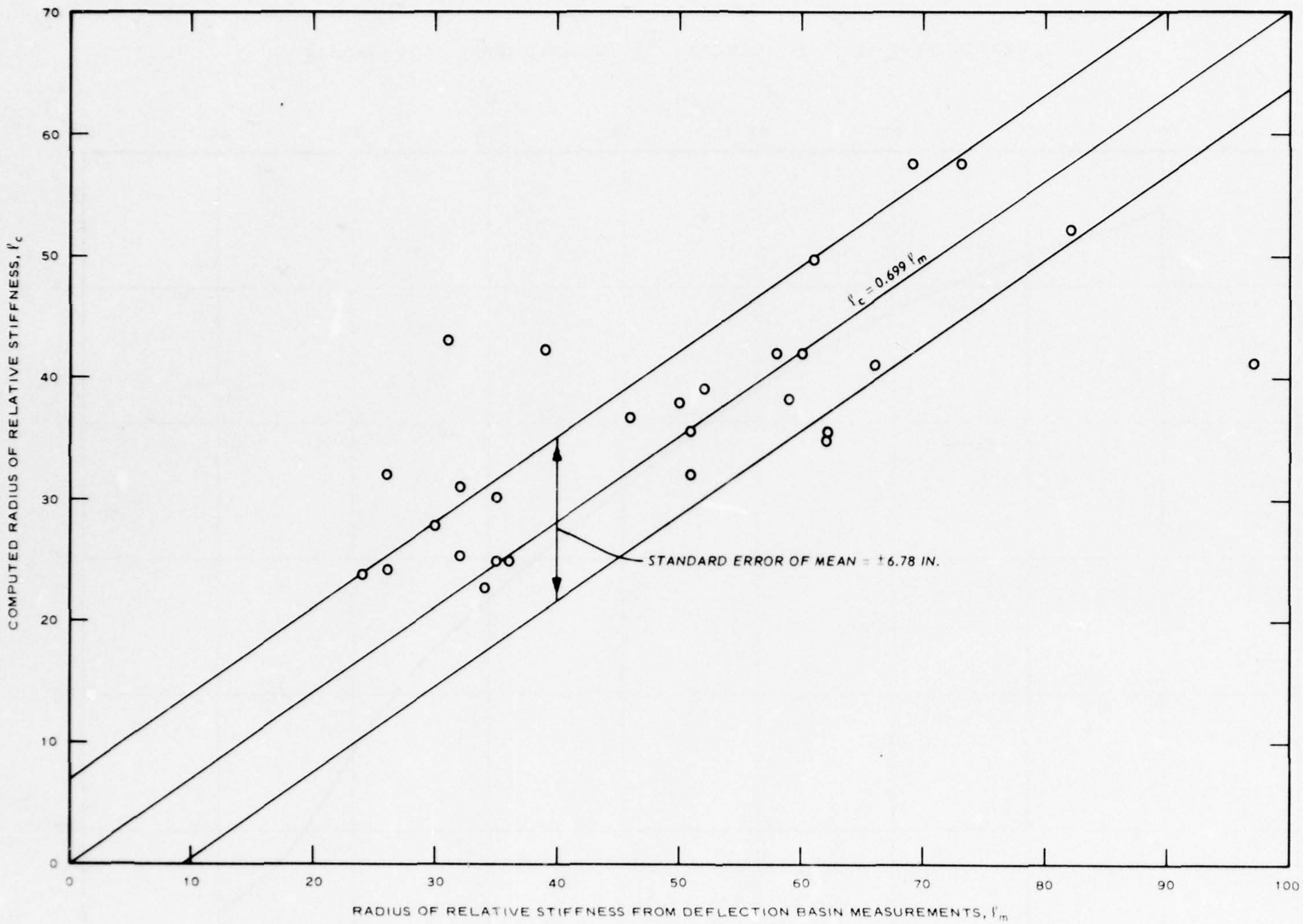

Figure 16. Correlation between radius of relative stiffness from deflection measurements and radius of relative stiffness computed from pavement properties

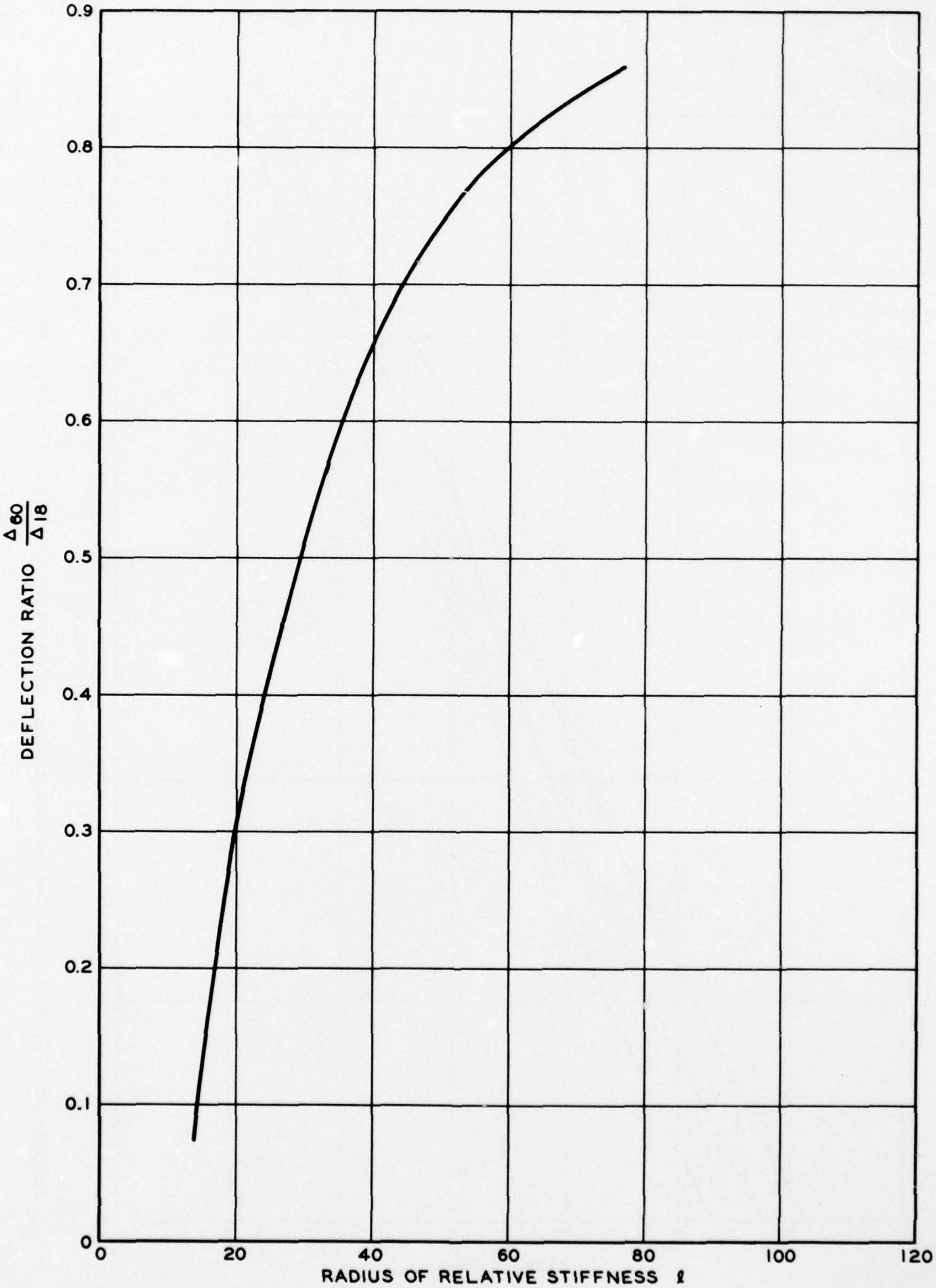

Figure 17. Determination of radius of relative stiffness ℓ

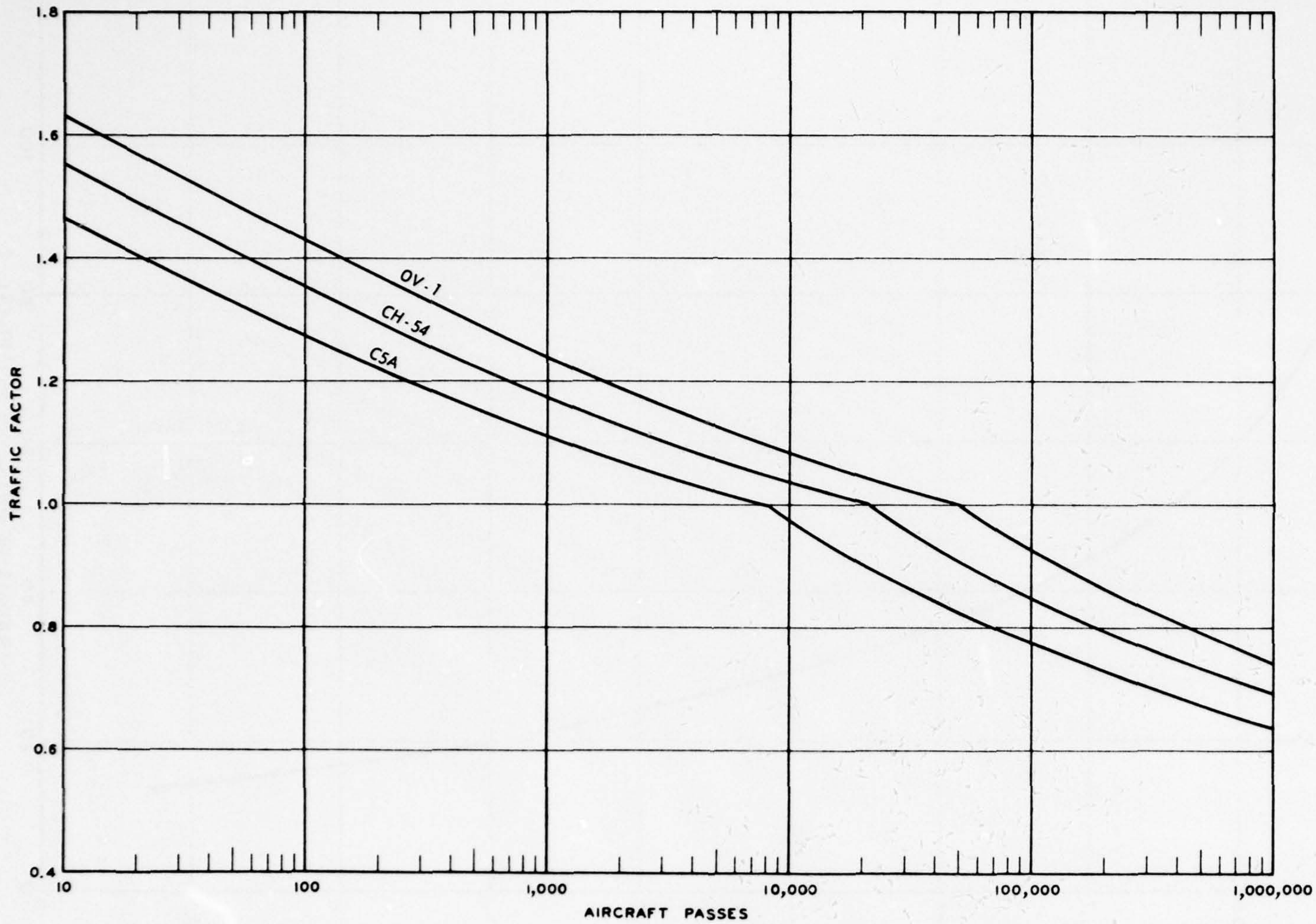

Figure 18. Traffic factor versus number of passes for OV-1, CH-54, and C-5A aircraft

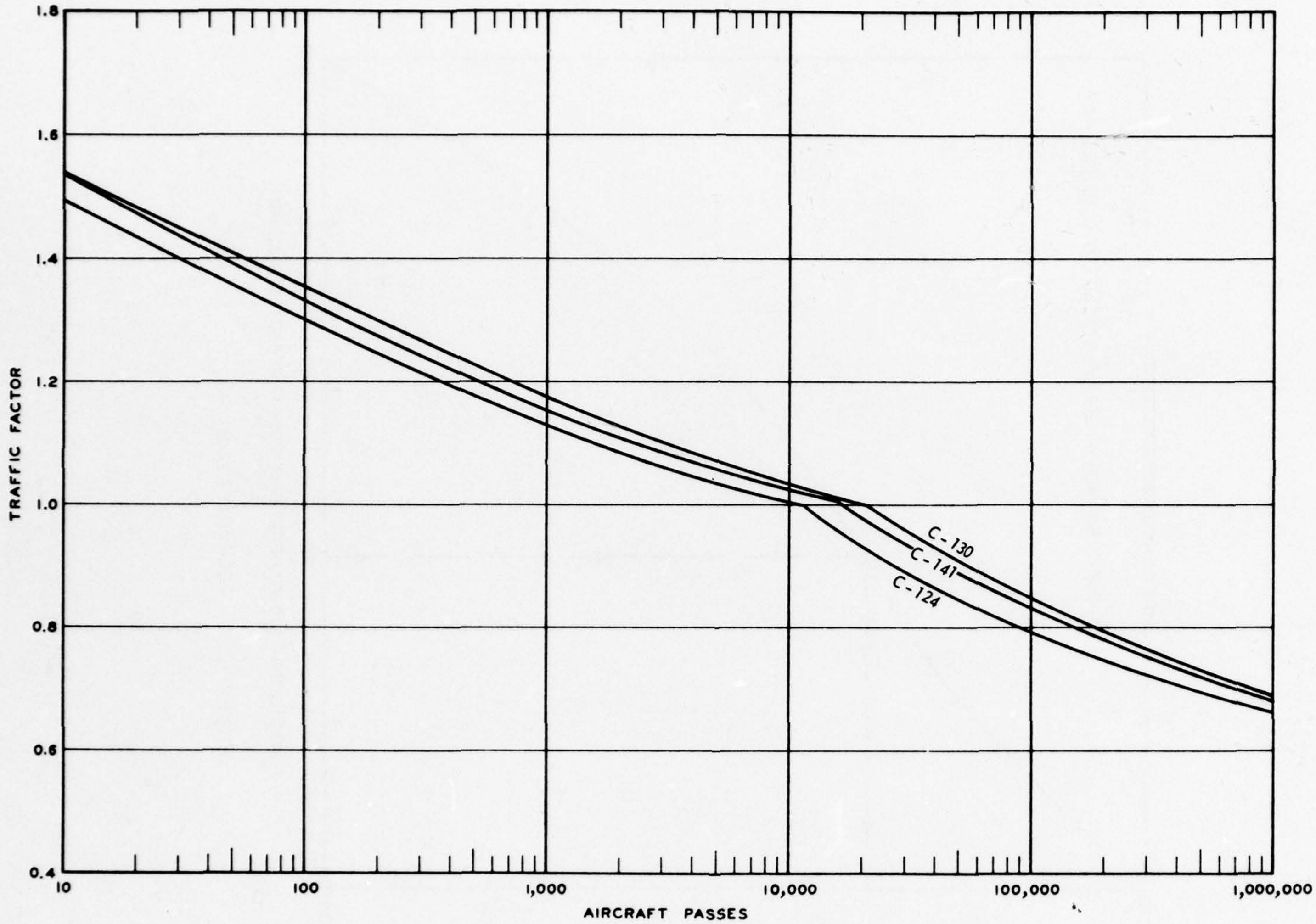

Figure 19. Traffic factor versus number of passes for C-130, C-141, and C-124 aircraft

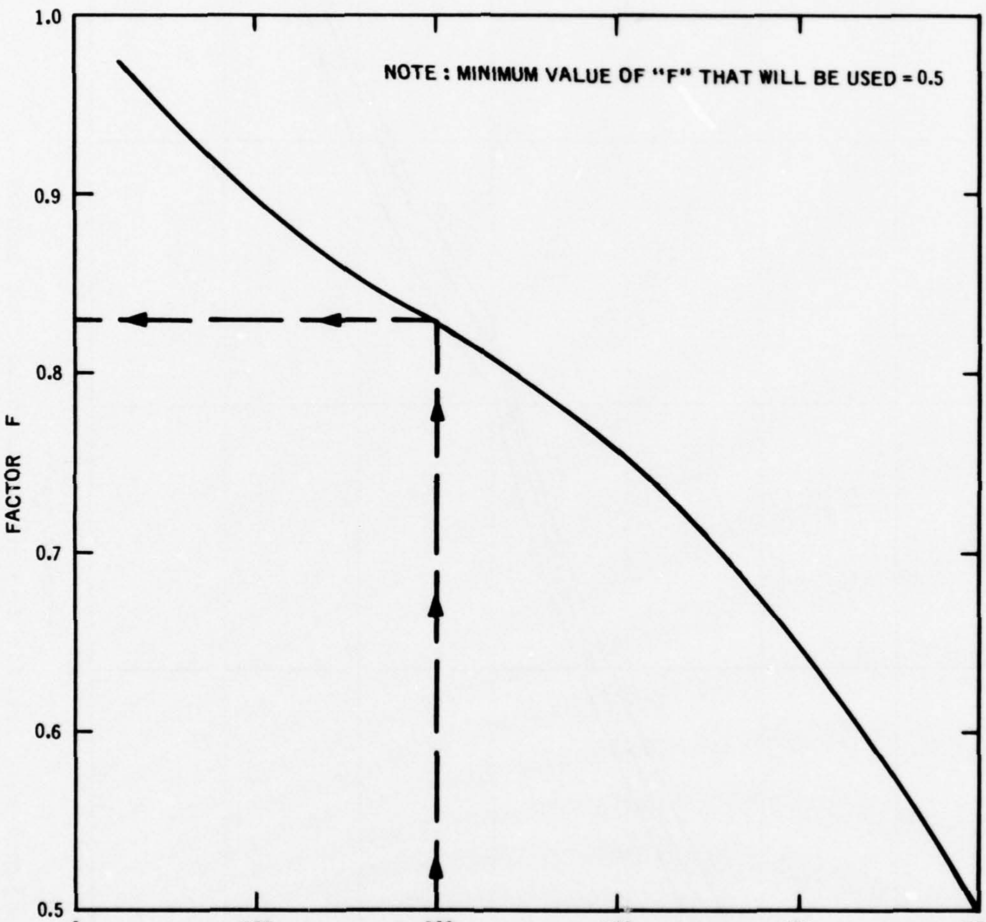

Figure 20. Determination of F factor

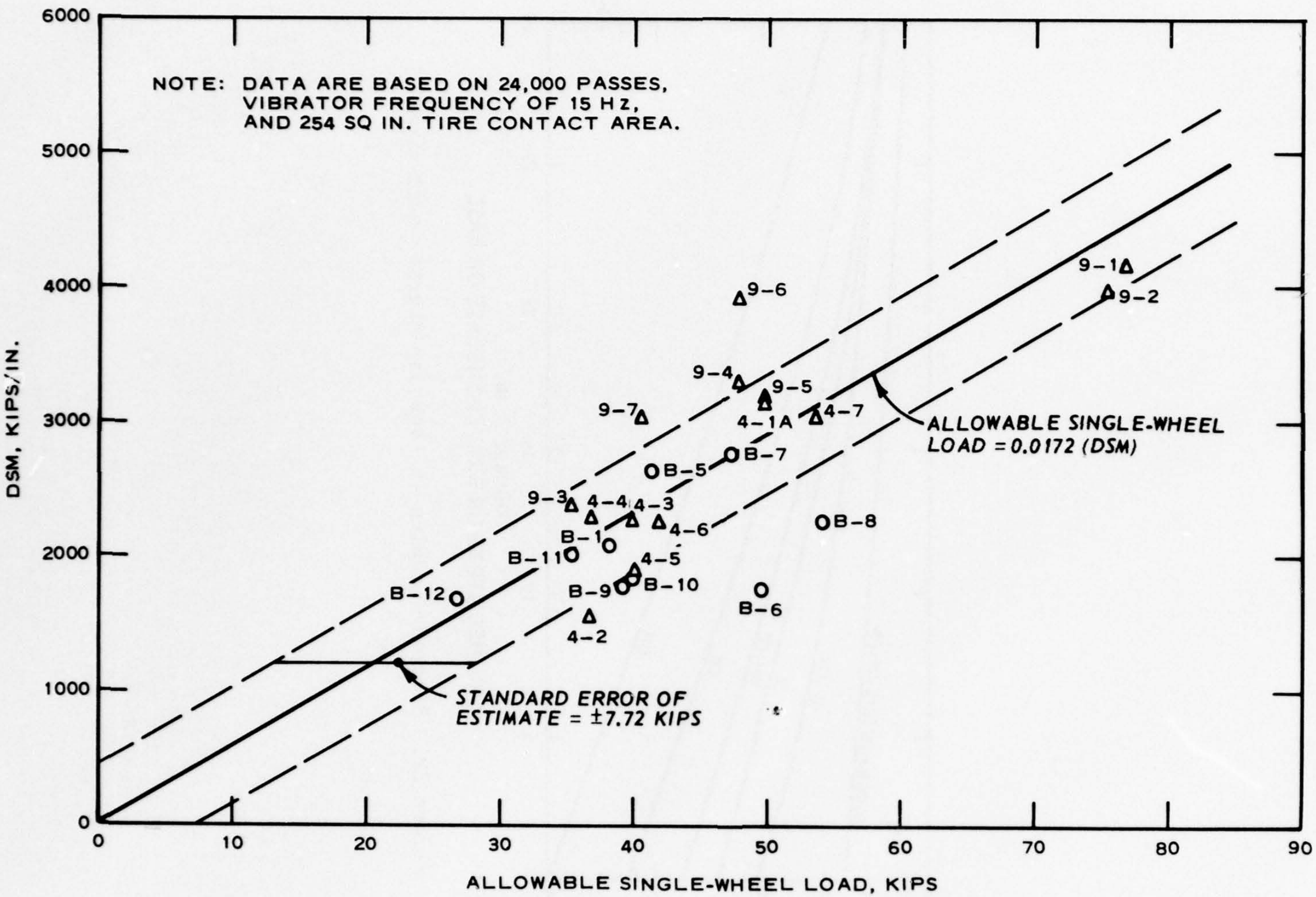

Figure 21. The DSM versus allowable single-wheel load for the AC over PCC pavements

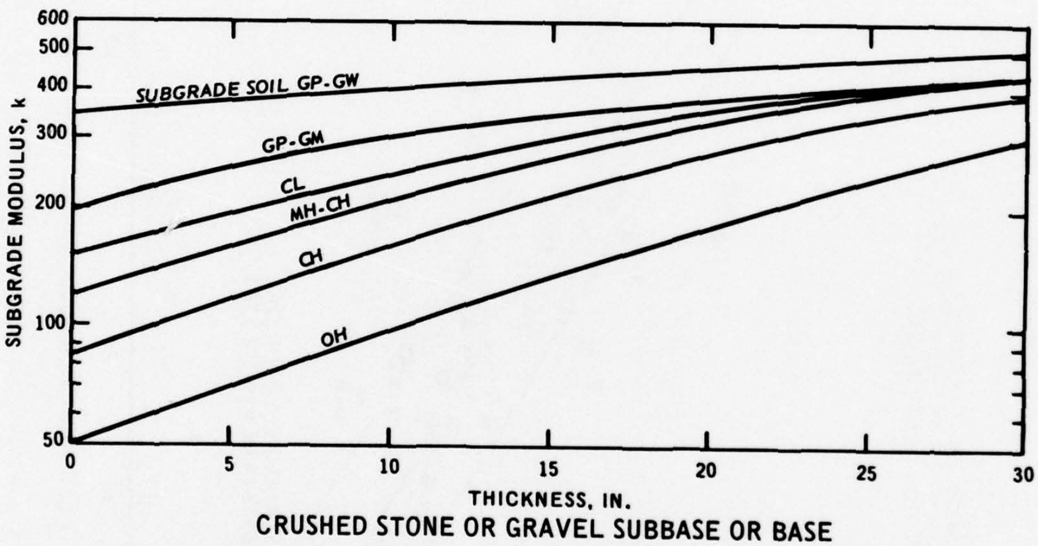

Figure 22. Subgrade modulus k versus subgrade soil type

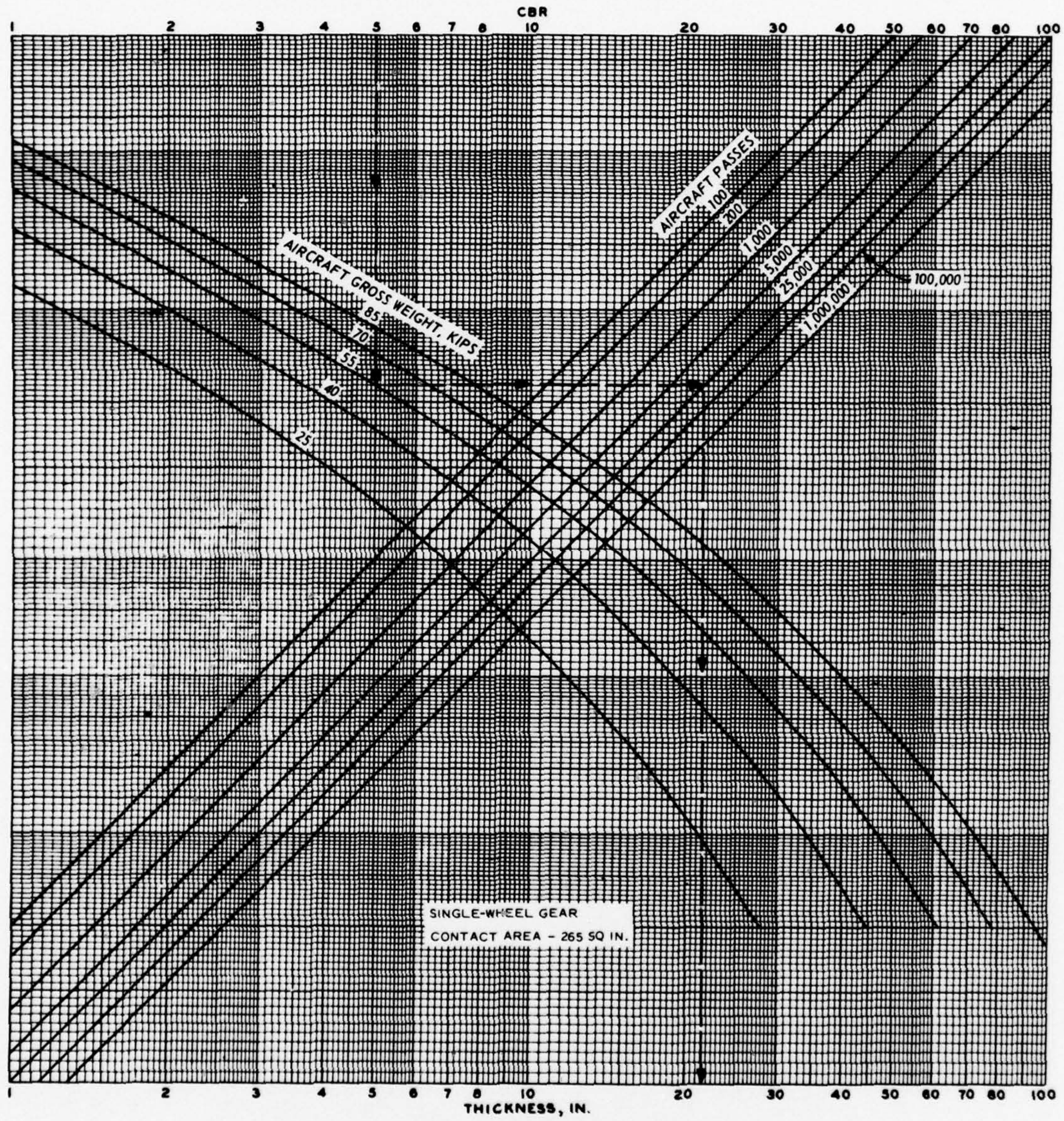

Figure 23. Flexible pavement design curves for army airfields, type B traffic areas (single-wheel gear, contact area - 265 sq in.)

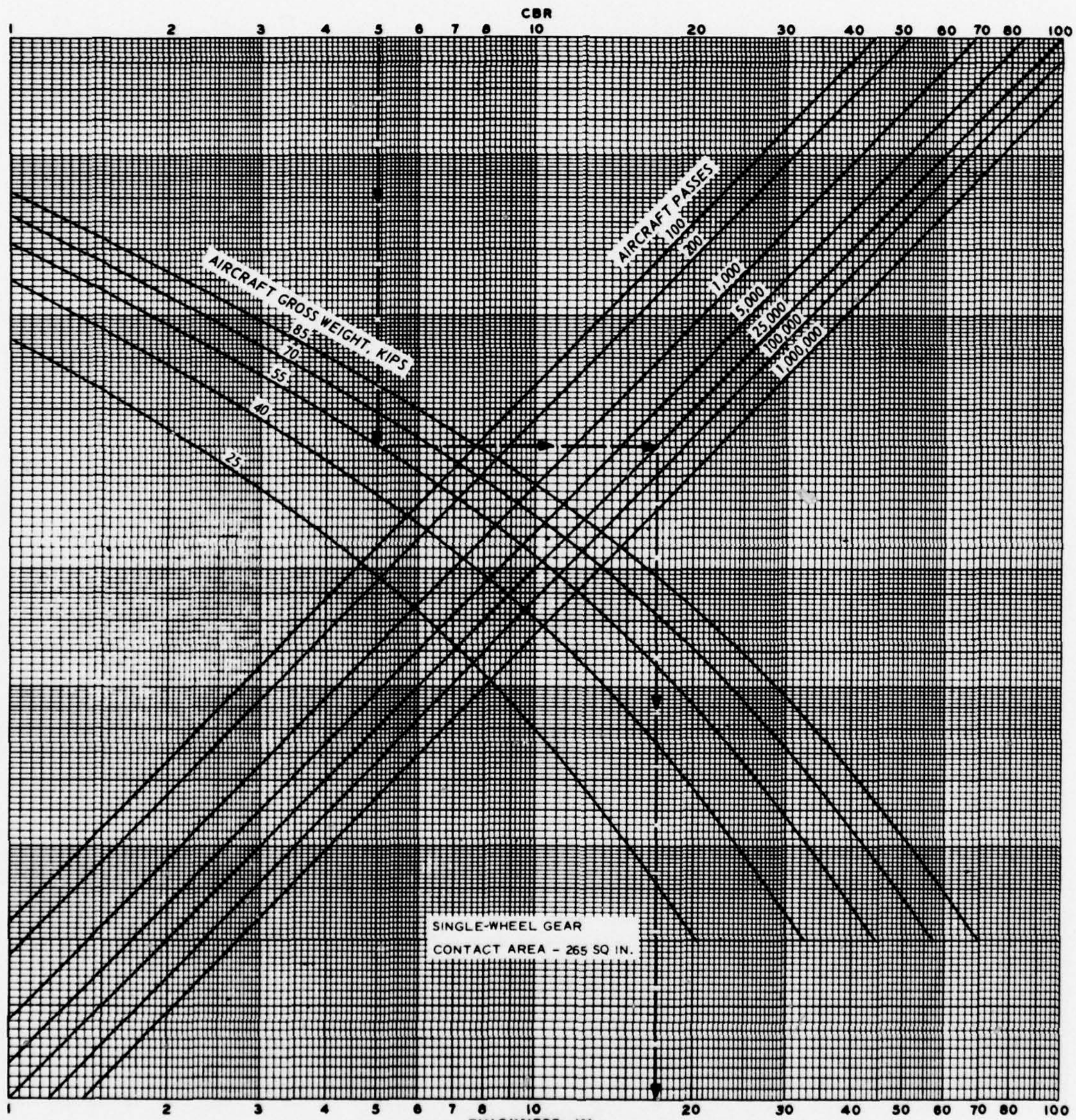

Figure 24. Flexible pavement design curves for army airfields, type C traffic areas (single-wheel gear, contact area - 265 sq in.)

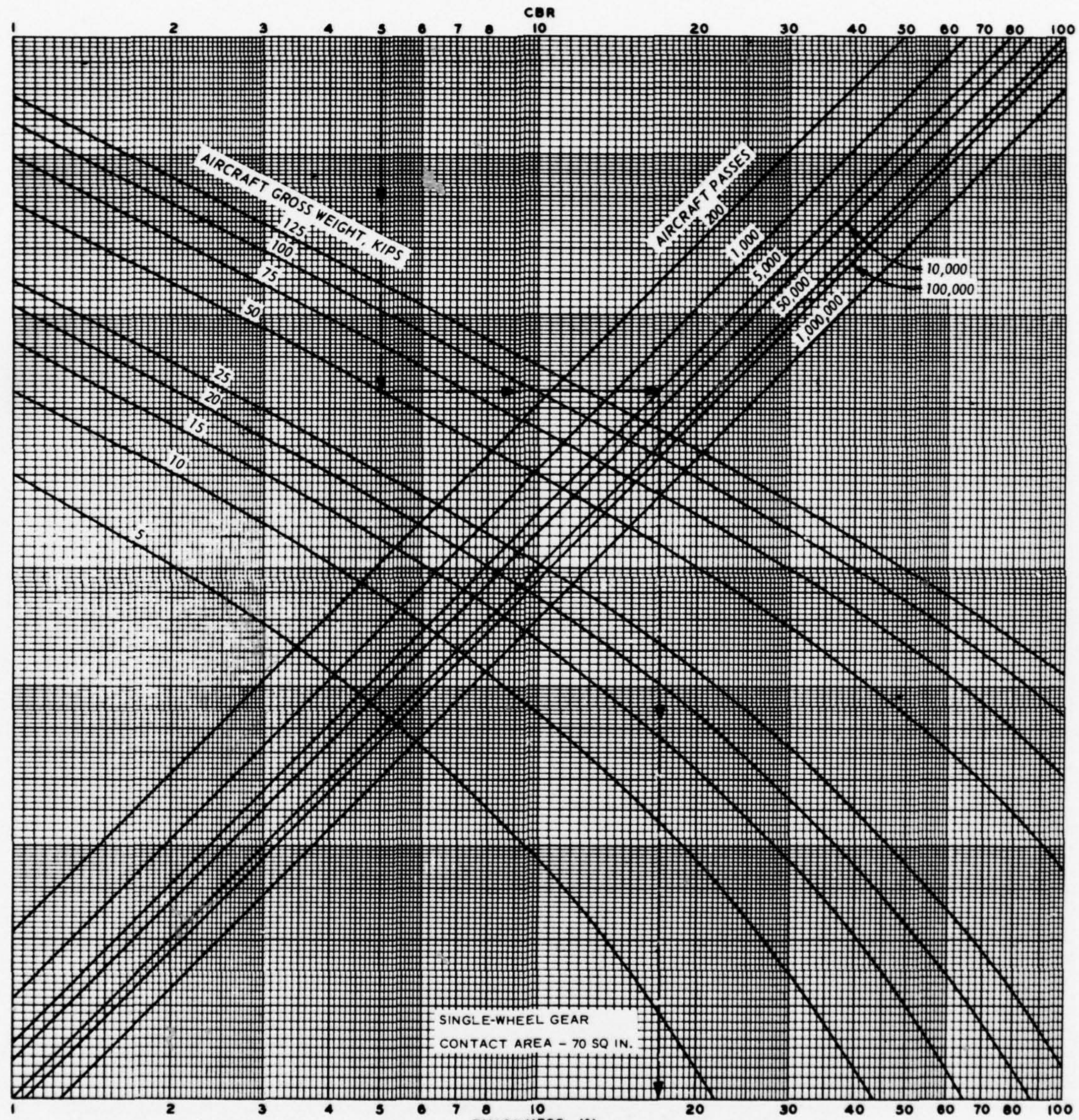

Figure 25. Flexible pavement design curves for army airfields, type B traffic areas (single-wheel gear, contact area - 70 sq in.)

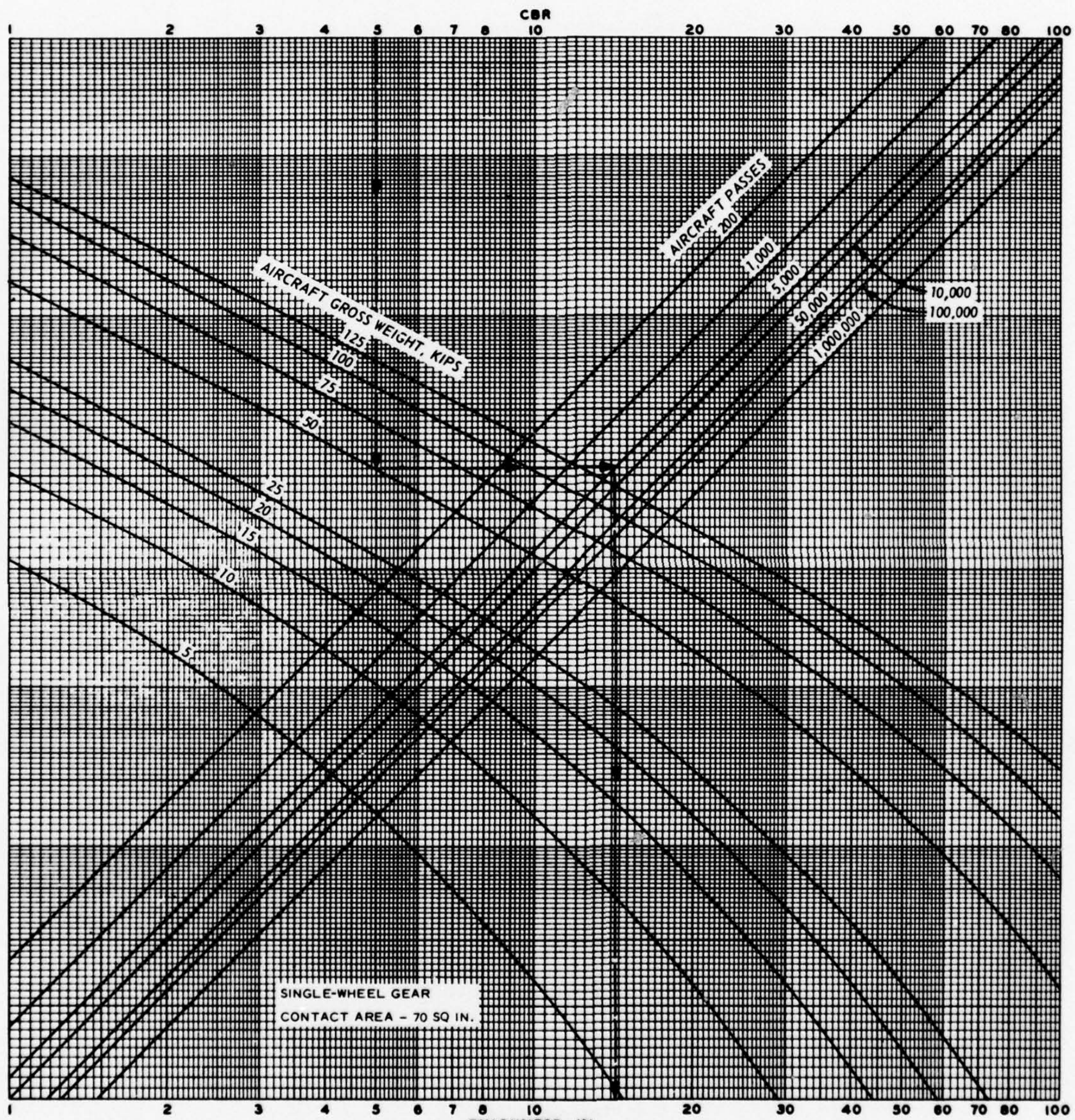

Figure 26. Flexible pavement design curves for army airfields, type C traffic areas (single-wheel gear, contact area - 70 sq in.)

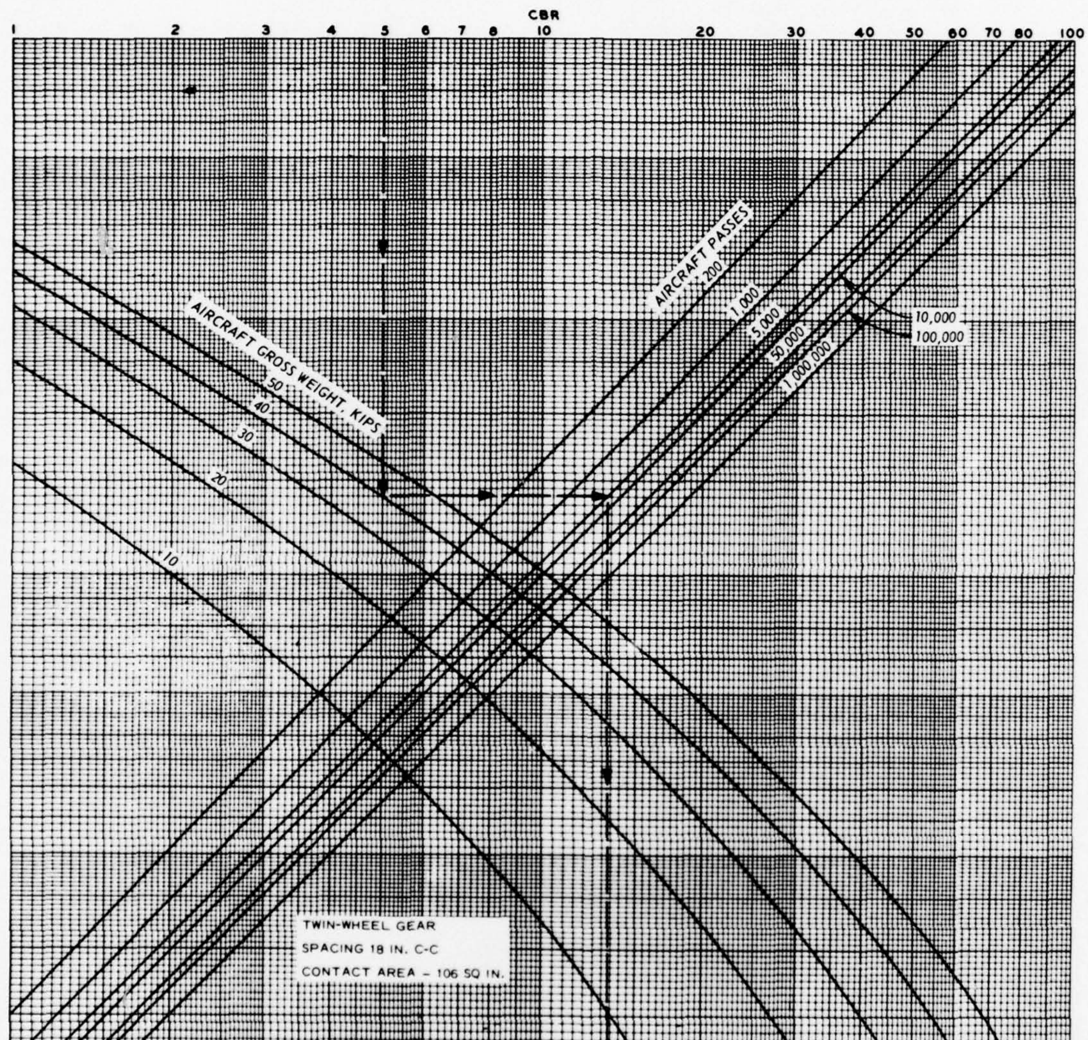

Figure 27. Flexible pavement design curves for army airfields, type B traffic areas (twin-wheel gear, contact area - 106 sq in.)

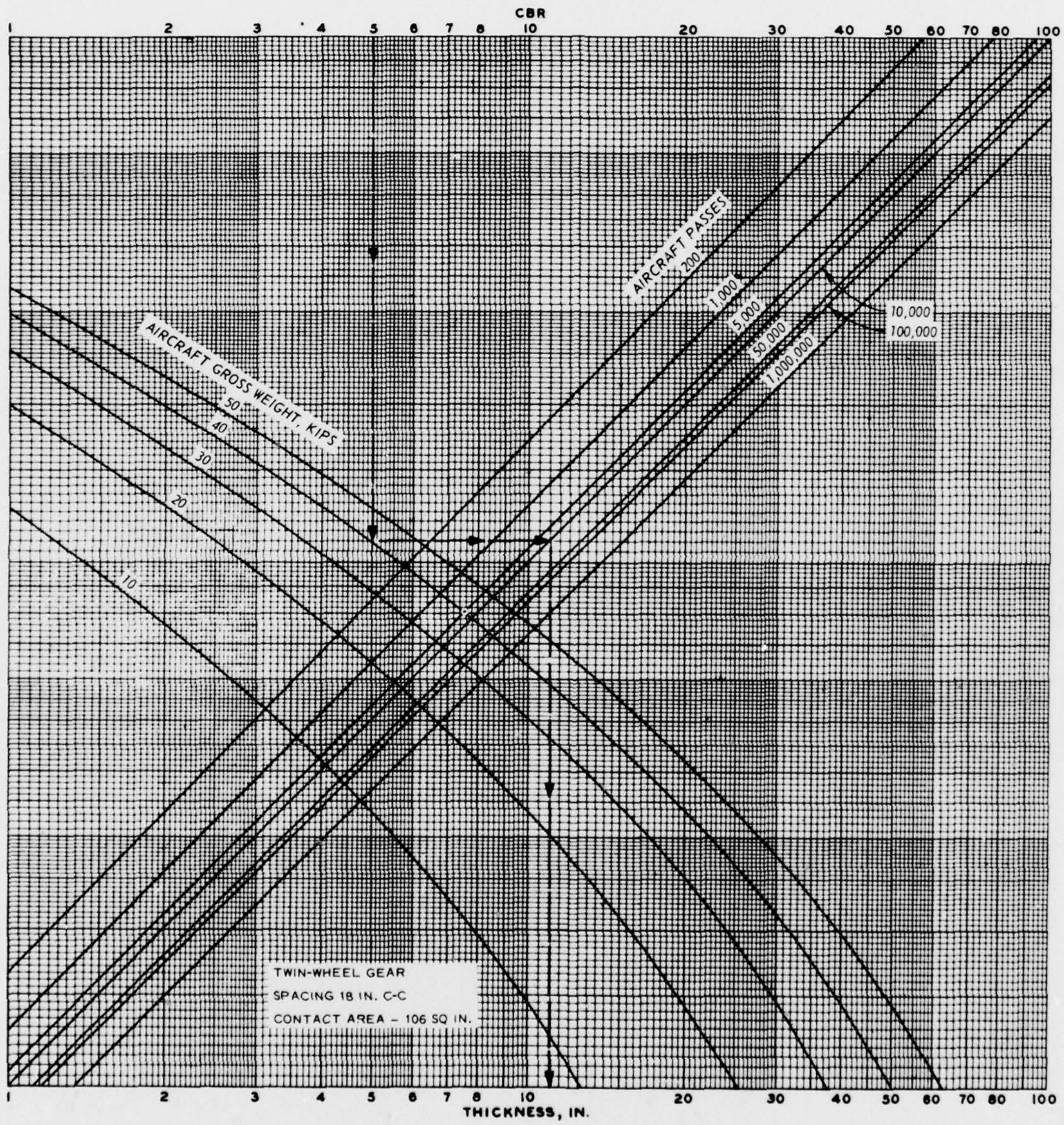

Figure 28. Flexible pavement design curves for army airfields, type C traffic areas (twin-wheel gear, contact area - 106 sq in.)

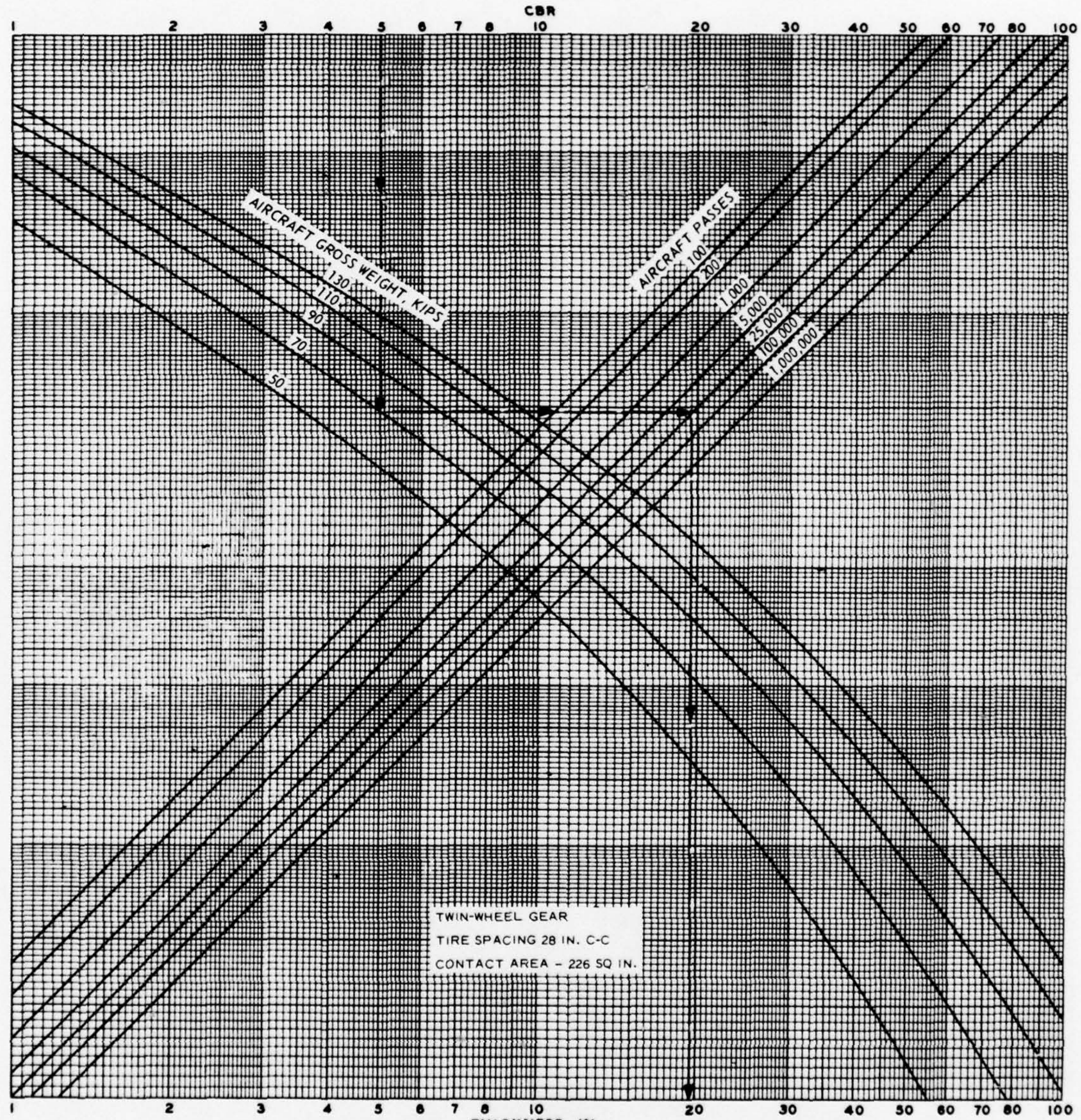

Figure 29. Flexible pavement design curves for army airfields, type B traffic areas (twin-wheel gear, contact area - 226 sq in.)

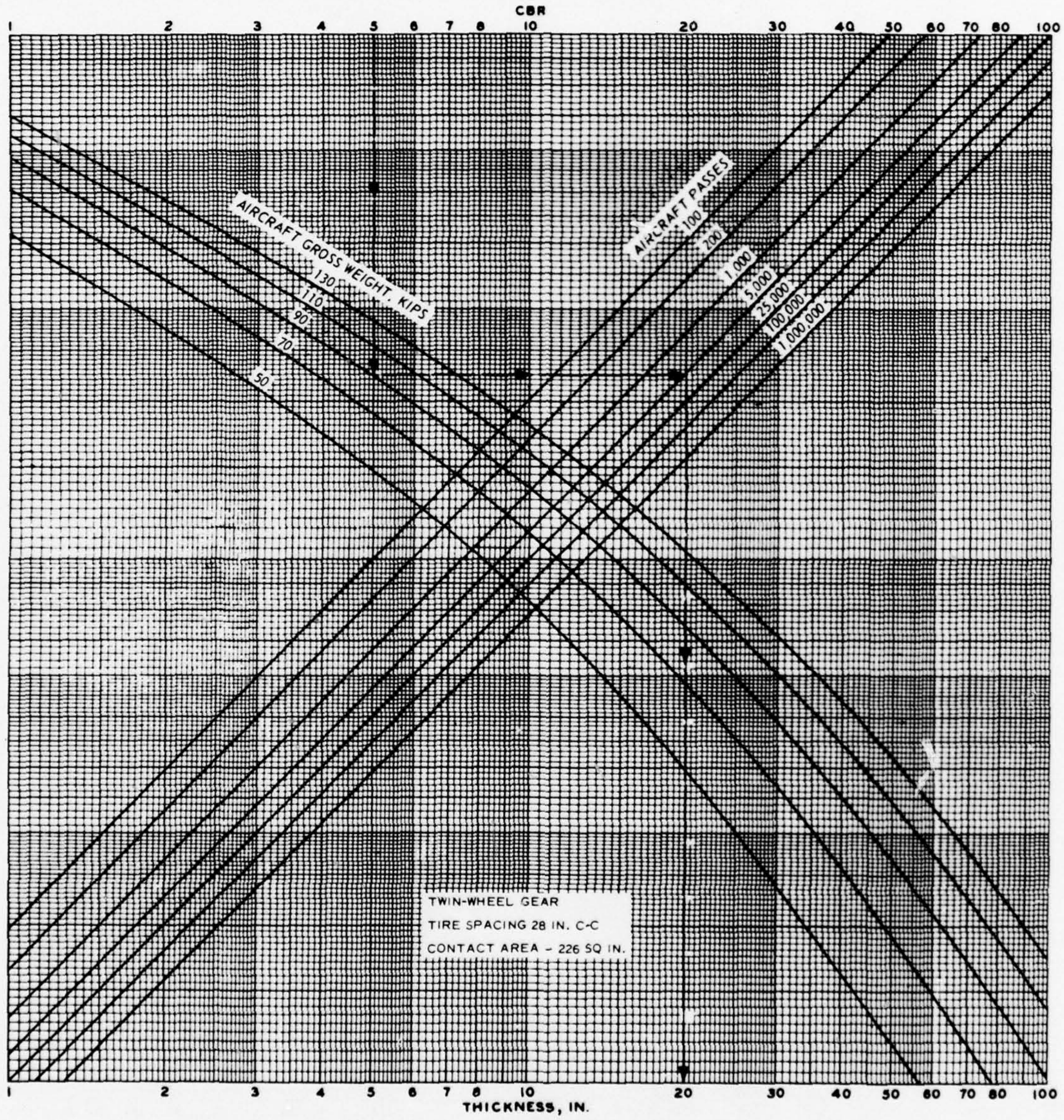

Figure 30. Flexible pavement design curves for army airfields, type C traffic areas (twin-wheel gear, contact area - 226 sq in.)

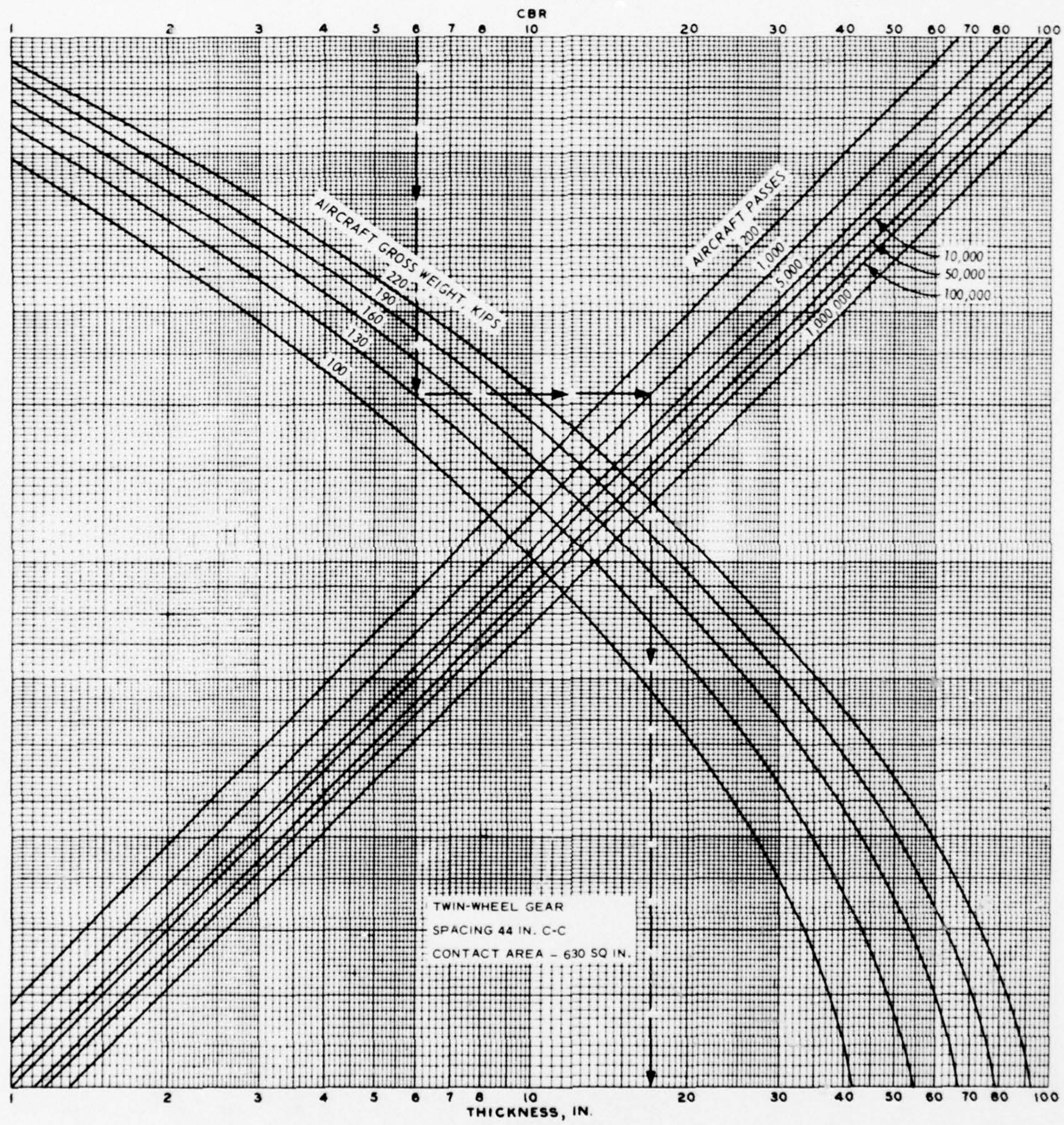

Figure 31. Flexible pavement design curves for army airfields, type B traffic areas (twin-wheel gear, contact area - 630 sq in.)

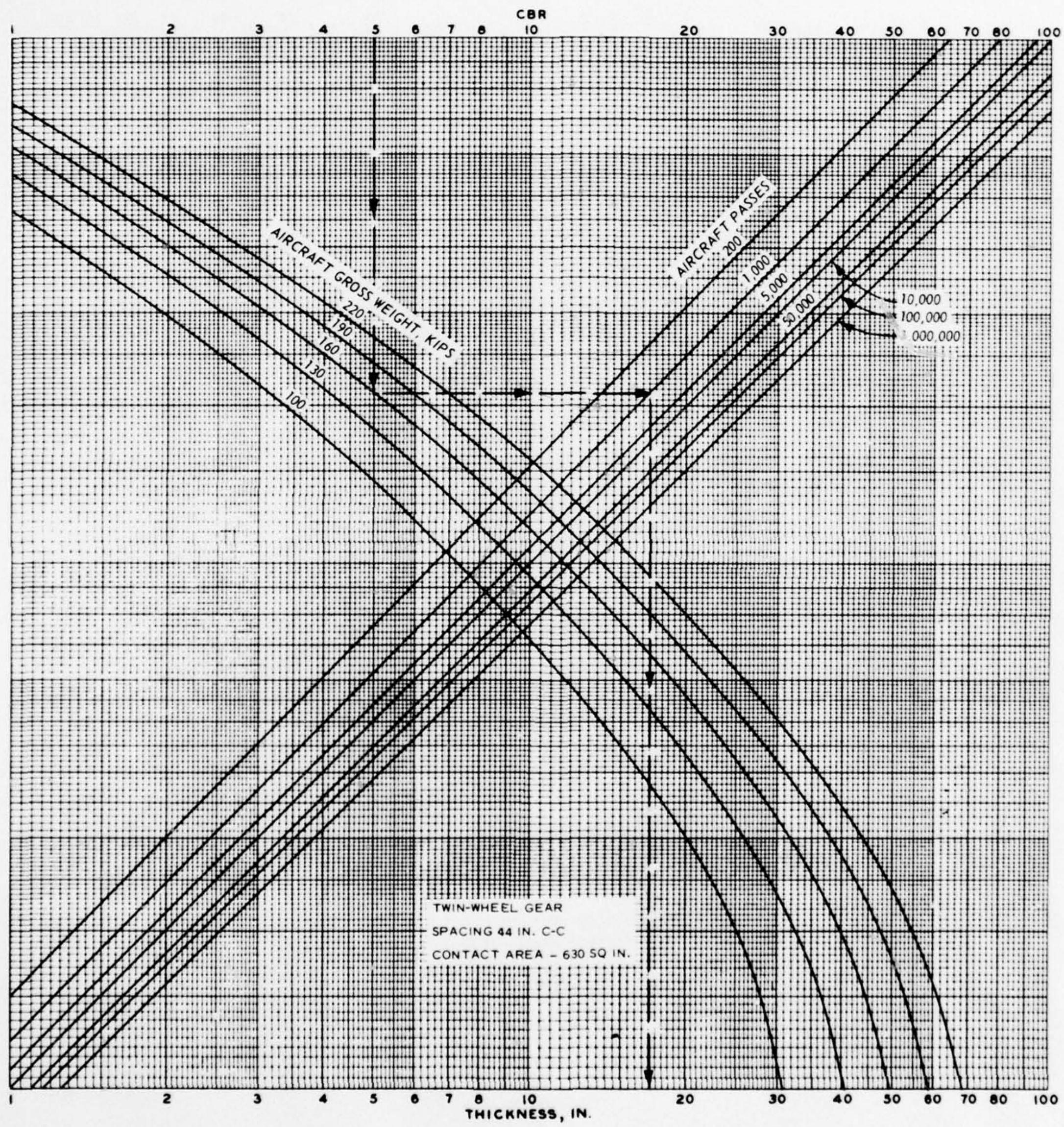

Figure 32. Flexible pavement design curves for army airfields, type C traffic areas (twin-wheel gear, contact area - 630 sq in.)

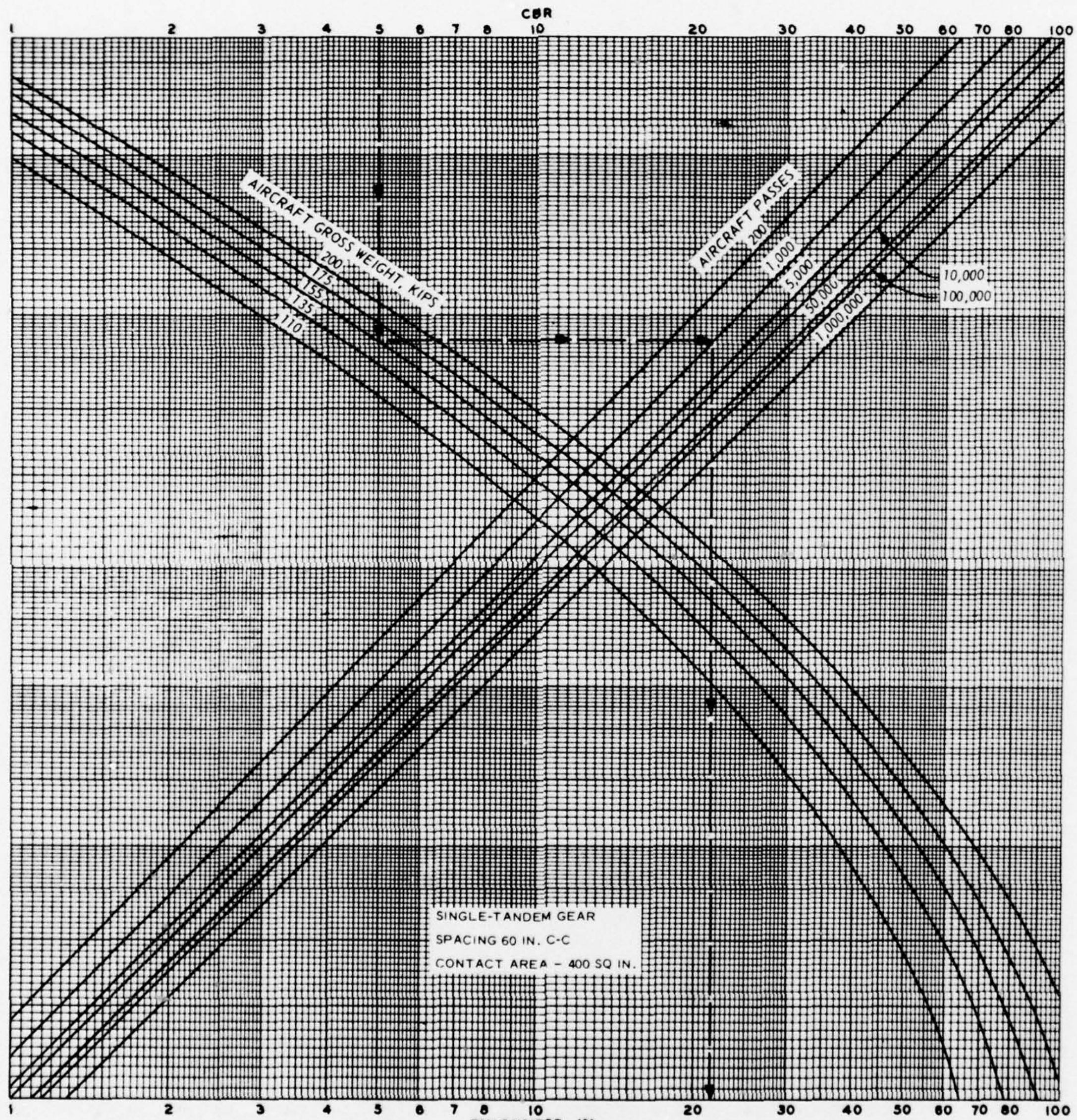

Figure 33. Flexible pavement design curves for army airfields, type B traffic areas (single-tandem gear, contact area - 400 sq in.)

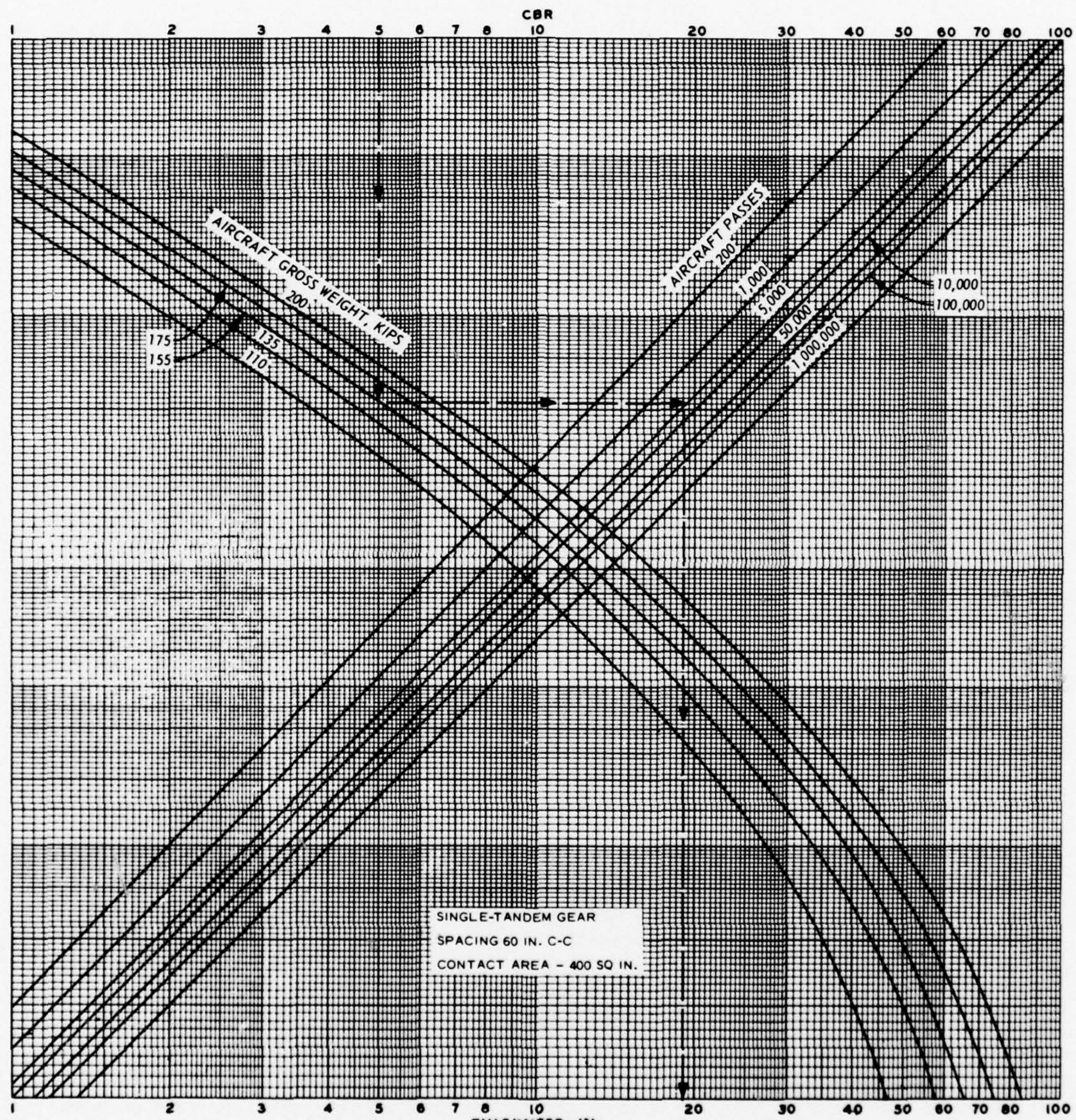

Figure 34. Flexible pavement design curves for army airfields, type C traffic areas (single-tandem gear, contact area - 400 sq in.)

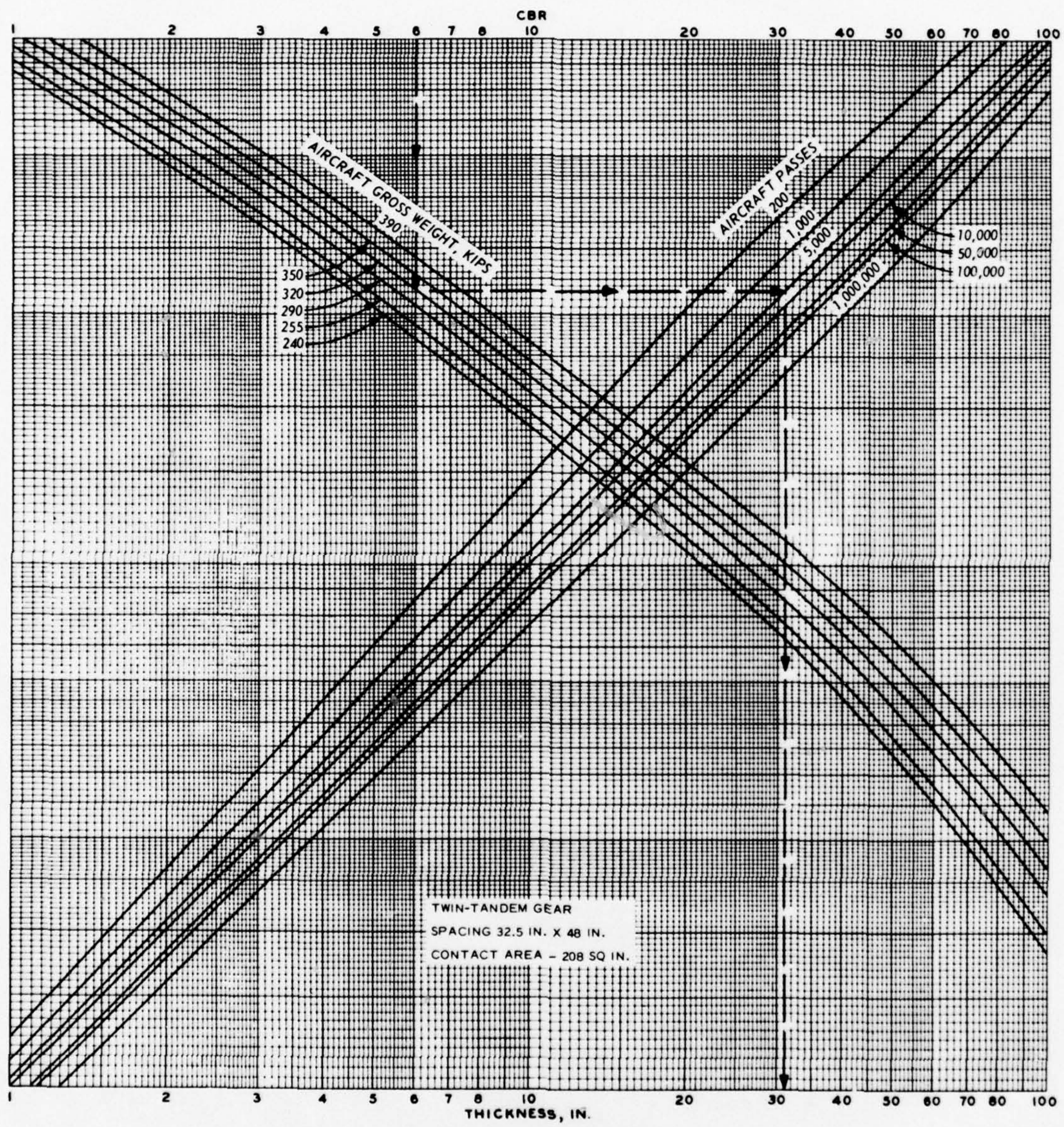

Figure 35. Flexible pavement design curves for army airfields, type B traffic areas (twin-tandem gear, contact area - 208 sq in.)

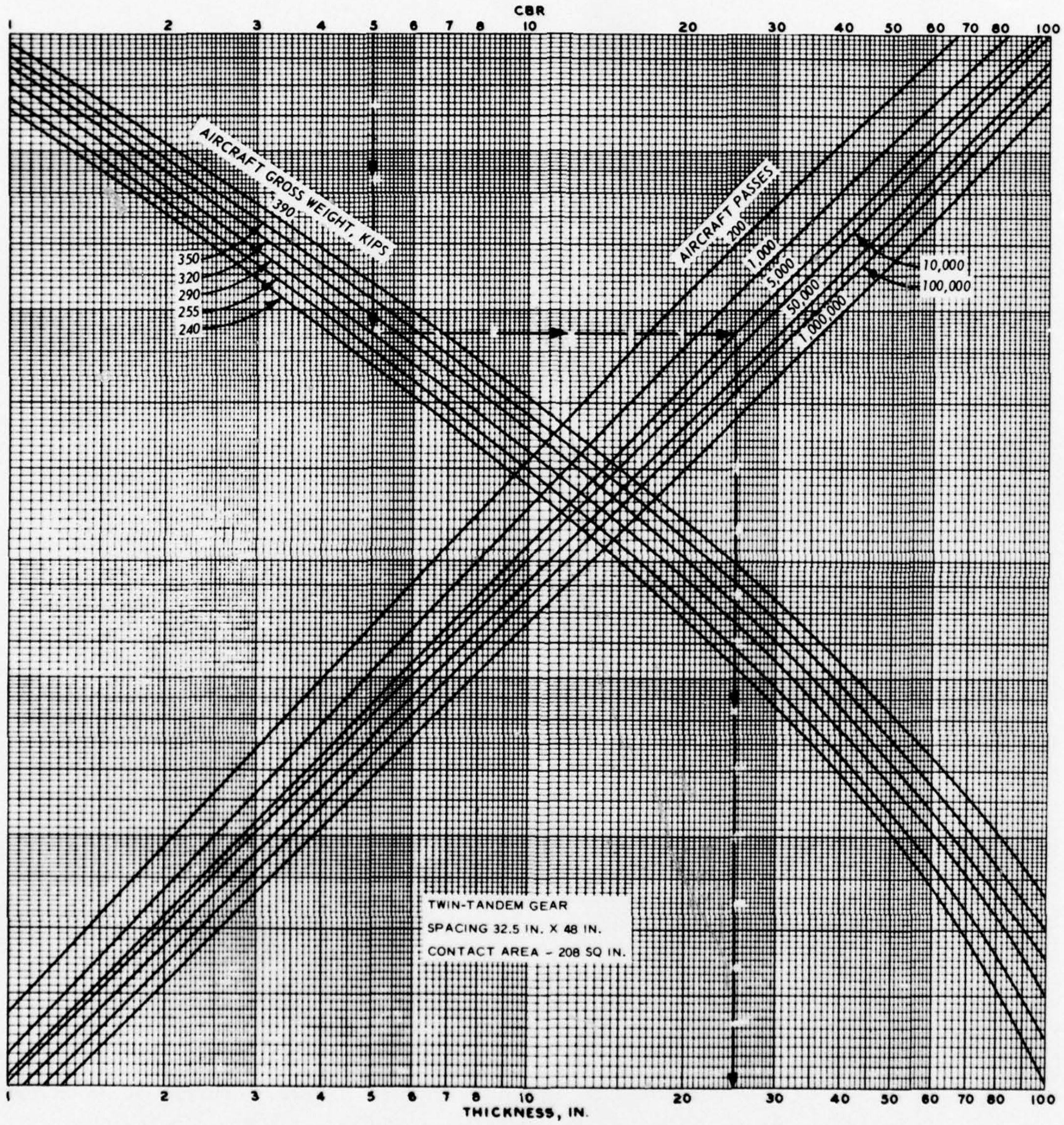

Figure 36. Flexible pavement design curves for army airfields, type C traffic areas (twin-tandem gear, contact area - 208 sq in.)

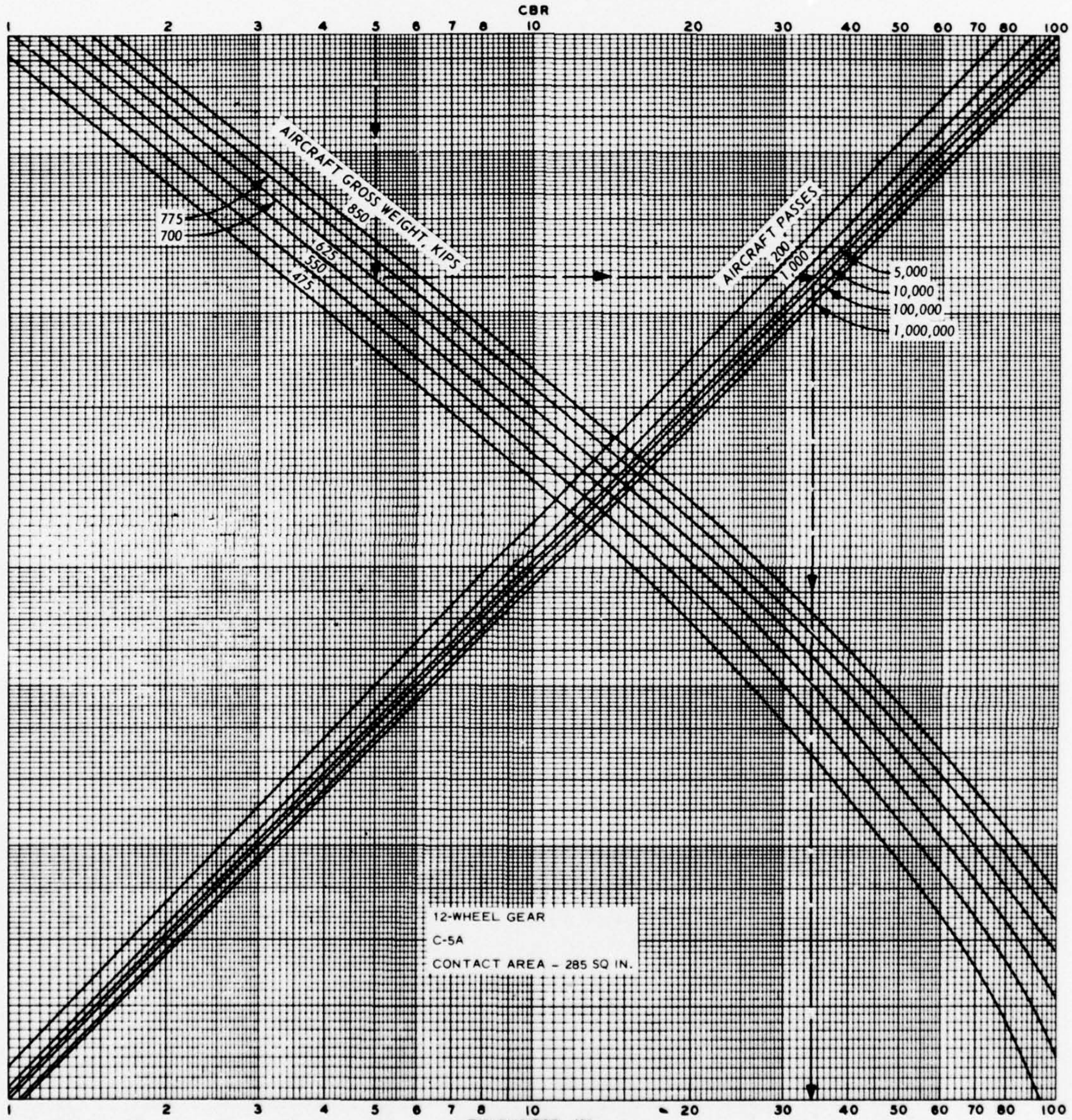

Figure 37. Flexible pavement design curves for army airfields, type B traffic areas (12-wheel gear, contact area - 285 sq in.)

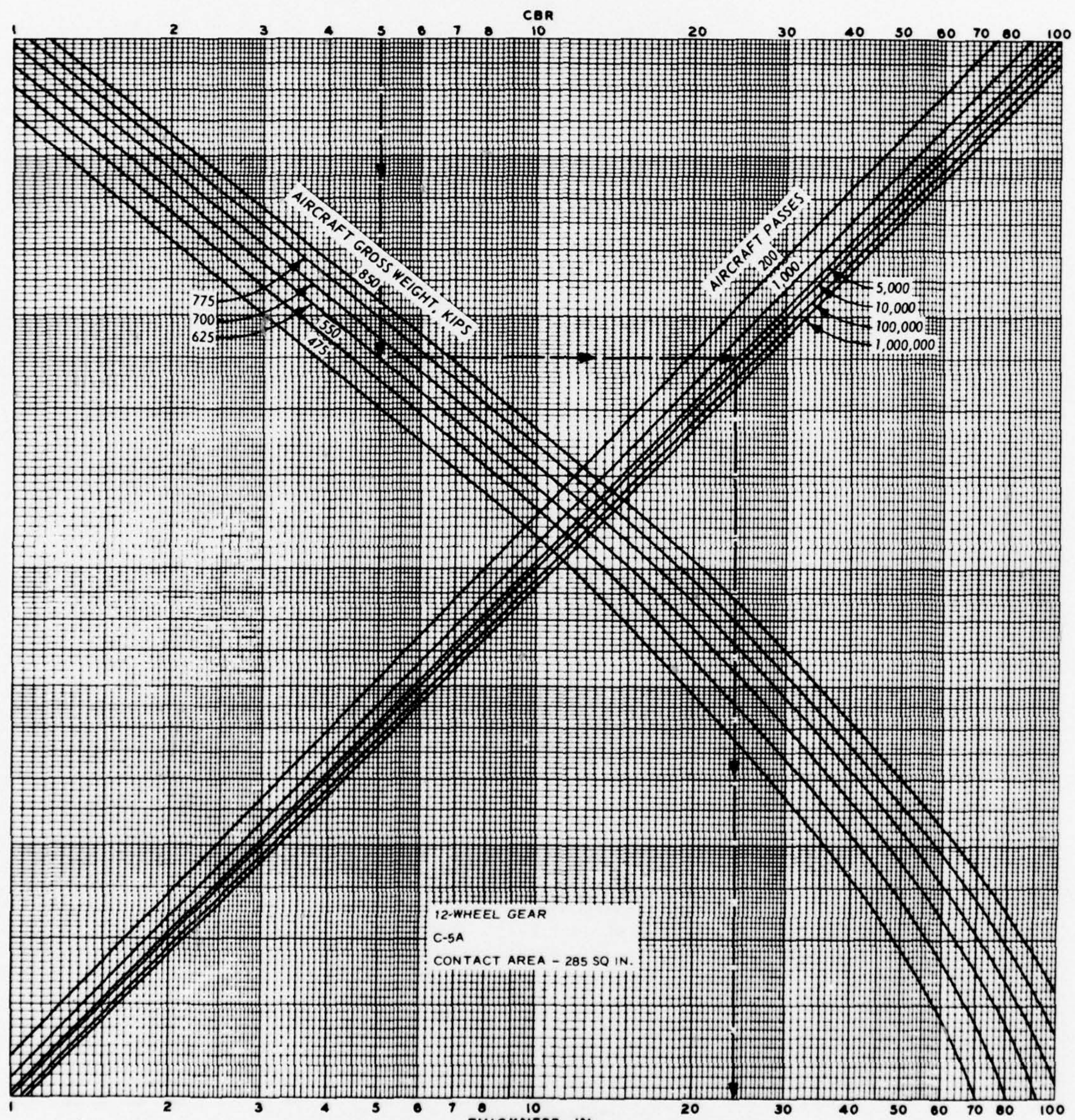

Figure 38. Flexible pavement design curves for army airfields, type C traffic areas (12-wheel gear, contact area - 285 sq in.)

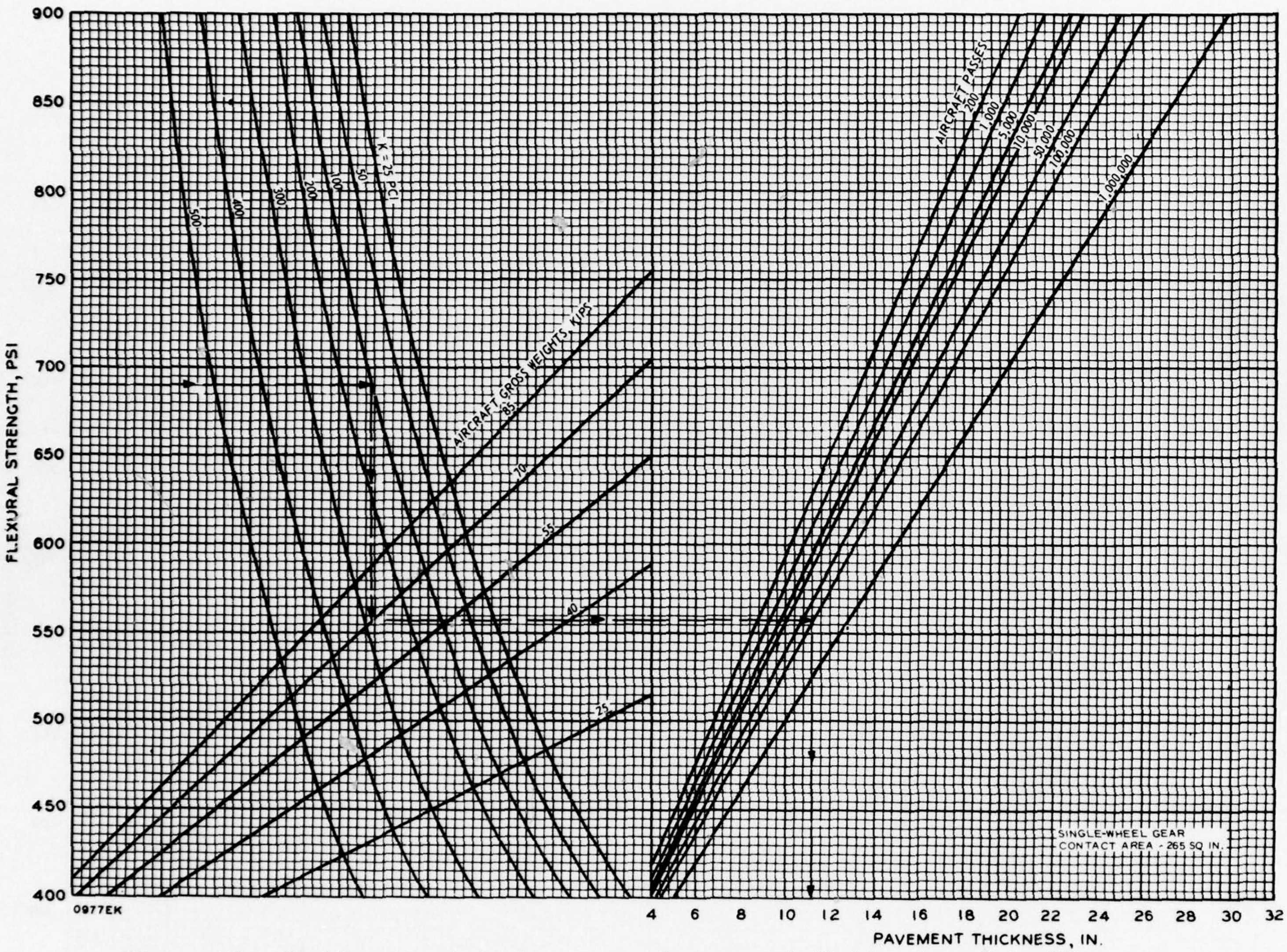

Figure 39. Rigid pavement design curves for army airfields, type B traffic areas (single-wheel gear, contact area - 265 sq in.)

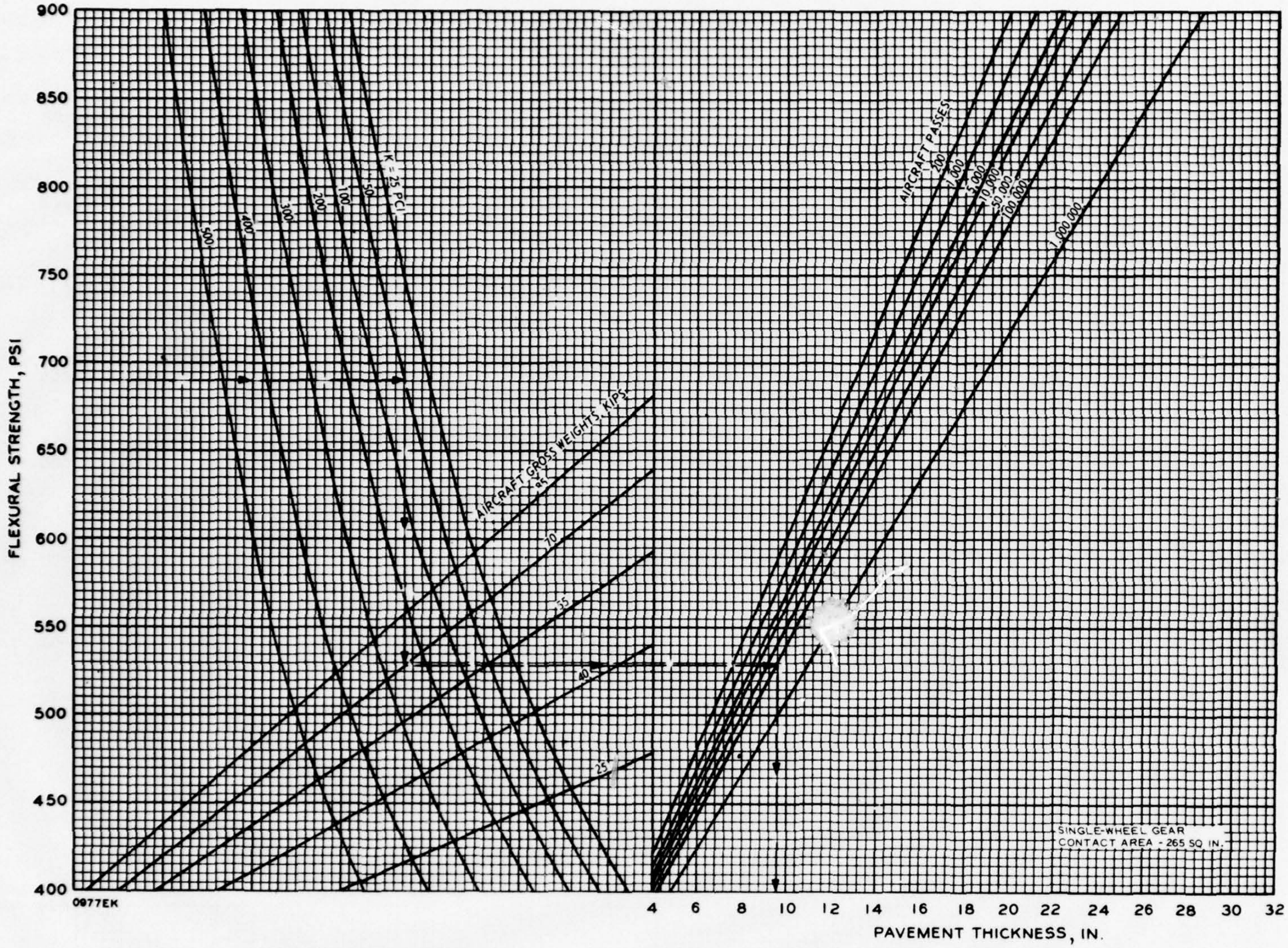

Figure 40. Rigid pavement design curves for army airfields, type C traffic areas (single-wheel gear, contact area - 265 sq in.)

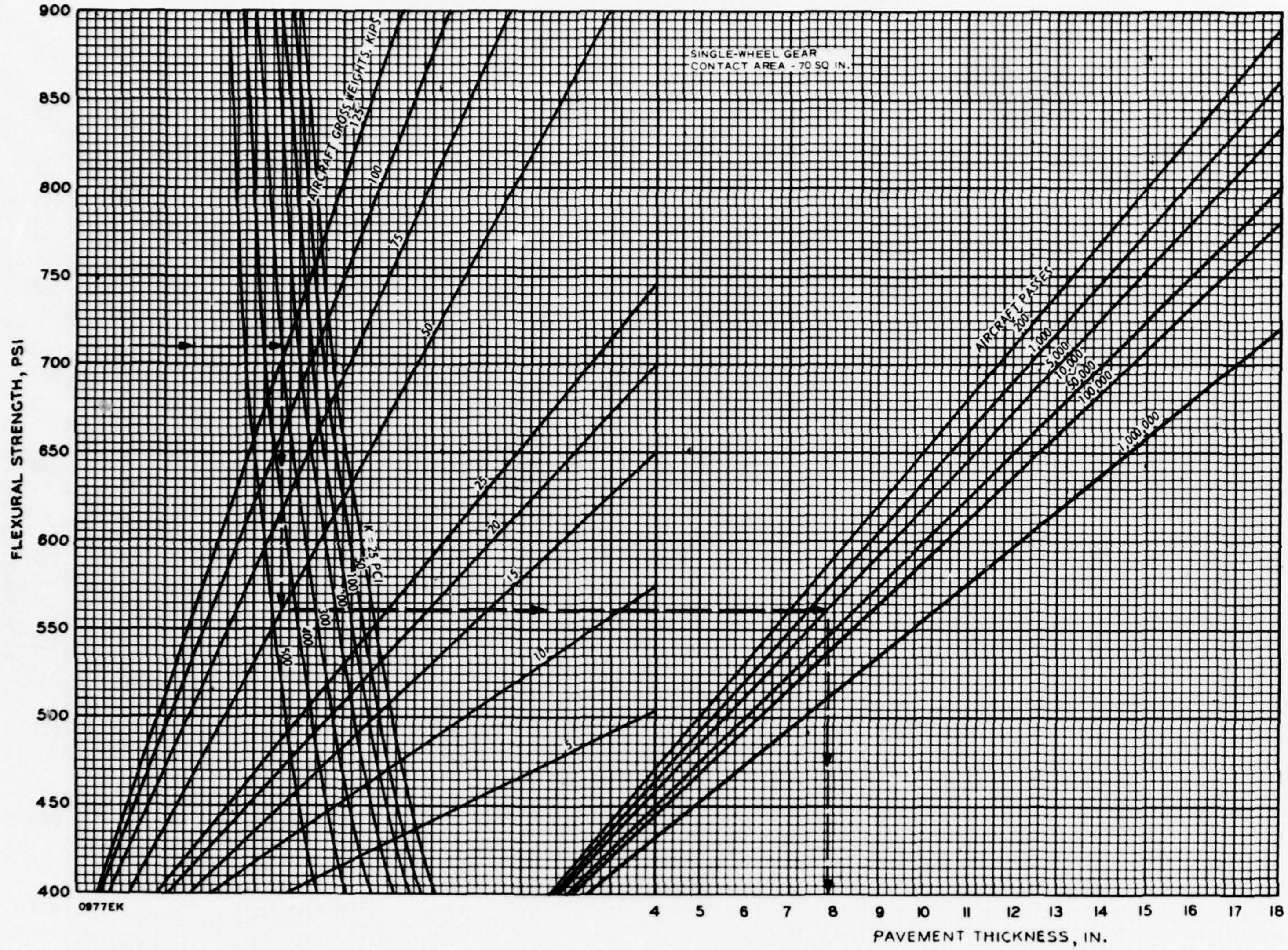

Figure 41. Rigid pavement design curves for army airfields, type B traffic areas (single-wheel gear, contact area - 70 sq in.)

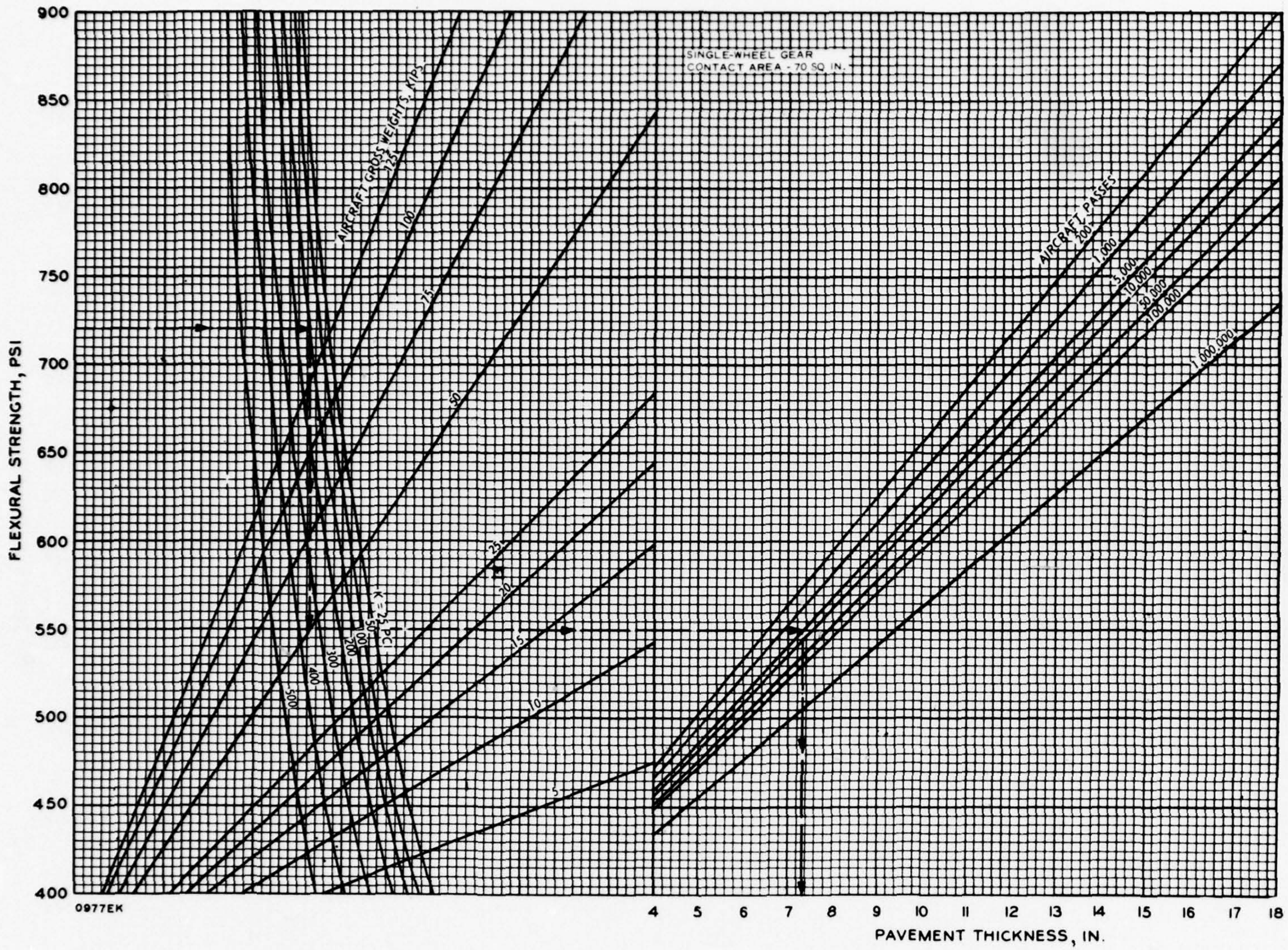

Figure 42. Rigid pavement design curves for army airfields, type C traffic areas (single-wheel gear, contact area - 70 sq in.)

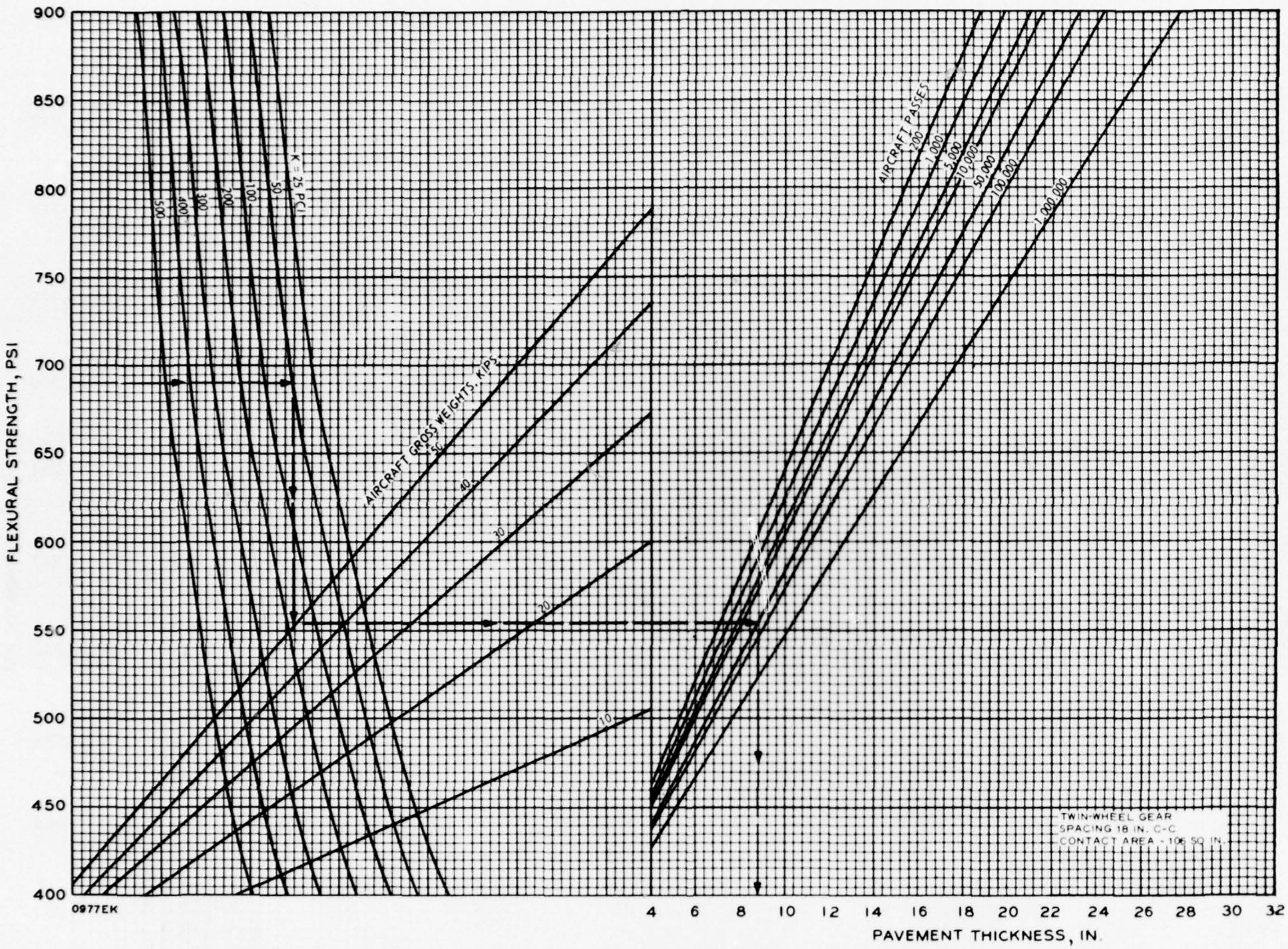

Figure 43. Rigid flexible pavement design curves for army airfields, type B traffic areas (twin-wheel gear, contact area - 106 sq in.)

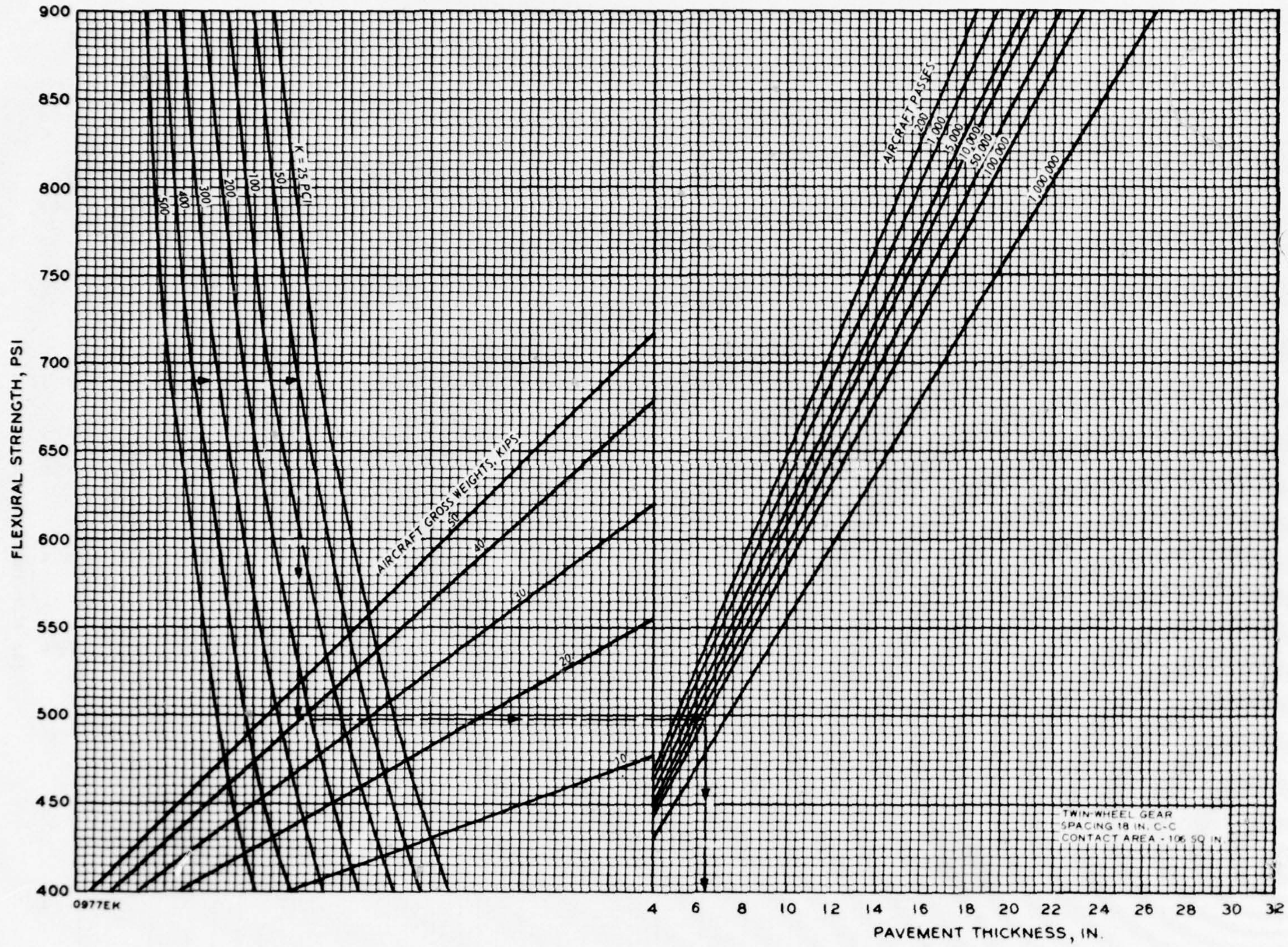

Figure 44. Rigid pavement design curves for army airfields, type C traffic areas (twin-wheel gear, contact area - 106 sq in.)

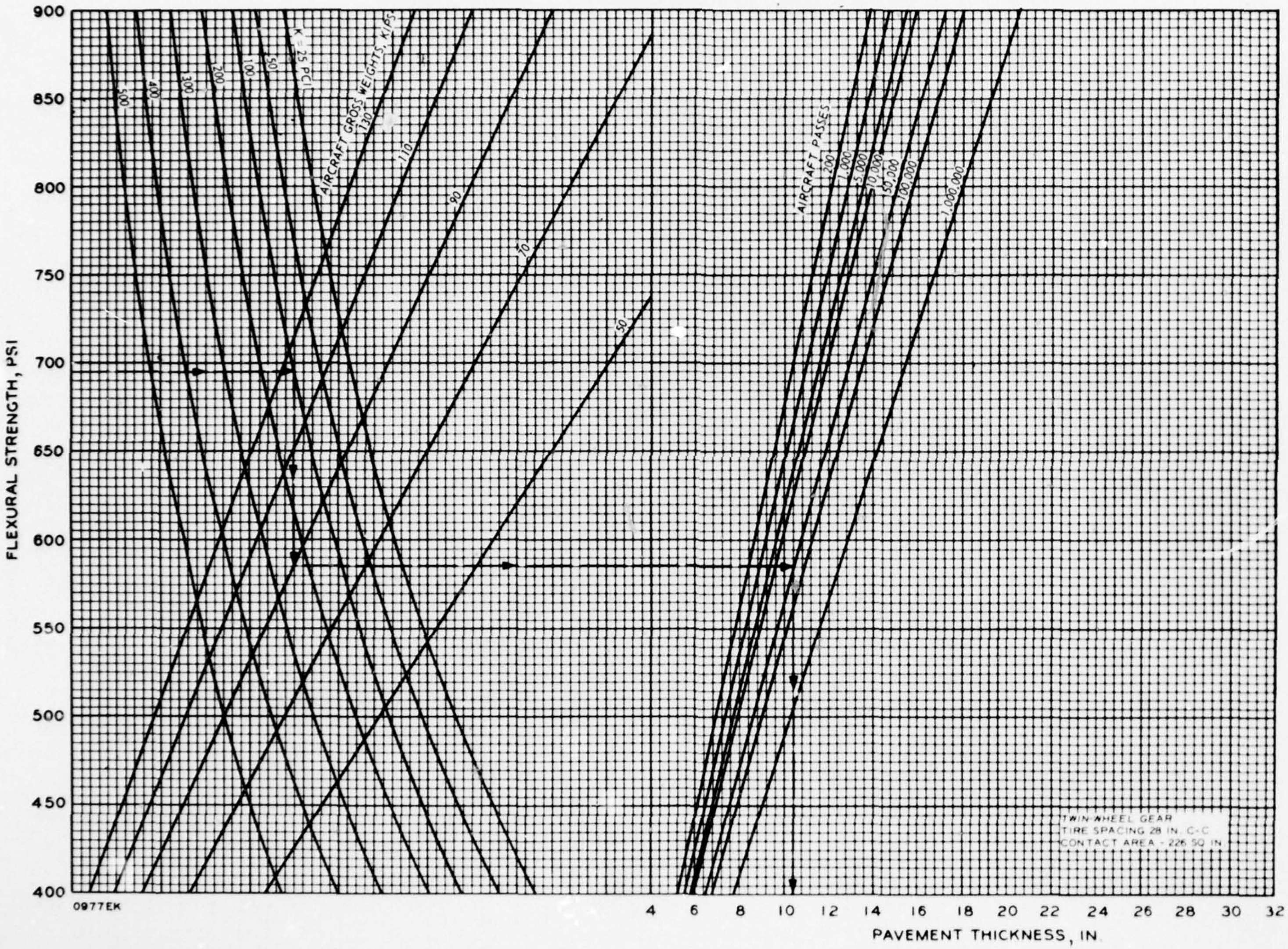

Figure 45. Rigid pavement design curves for army airfields, type B traffic areas (twin-wheel gear, contact area - 226 sq in.)

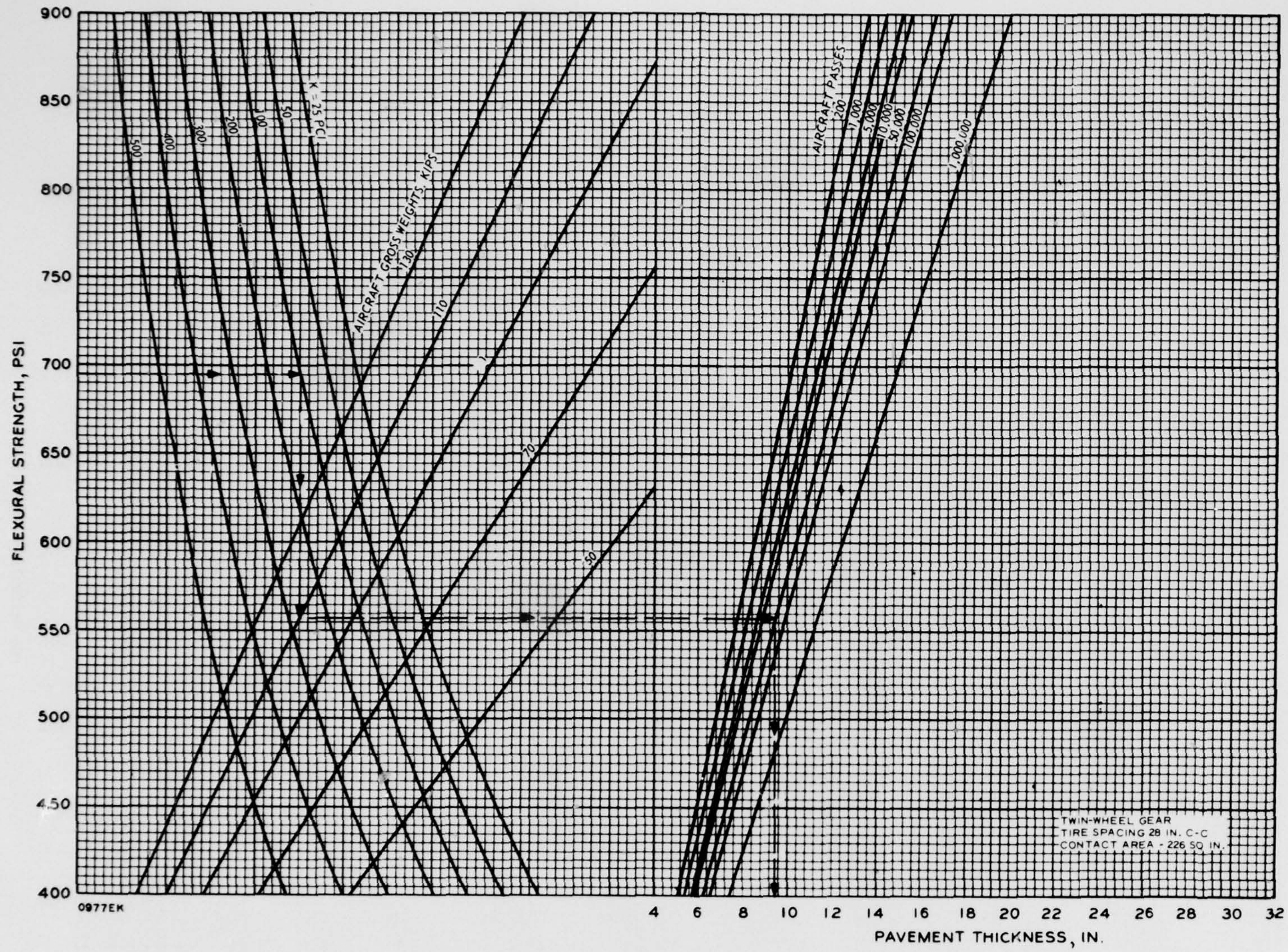

Figure 46. Rigid pavement design curves for army airfields, type C traffic areas (twin-wheel gear, contact area - 226 sq in.)

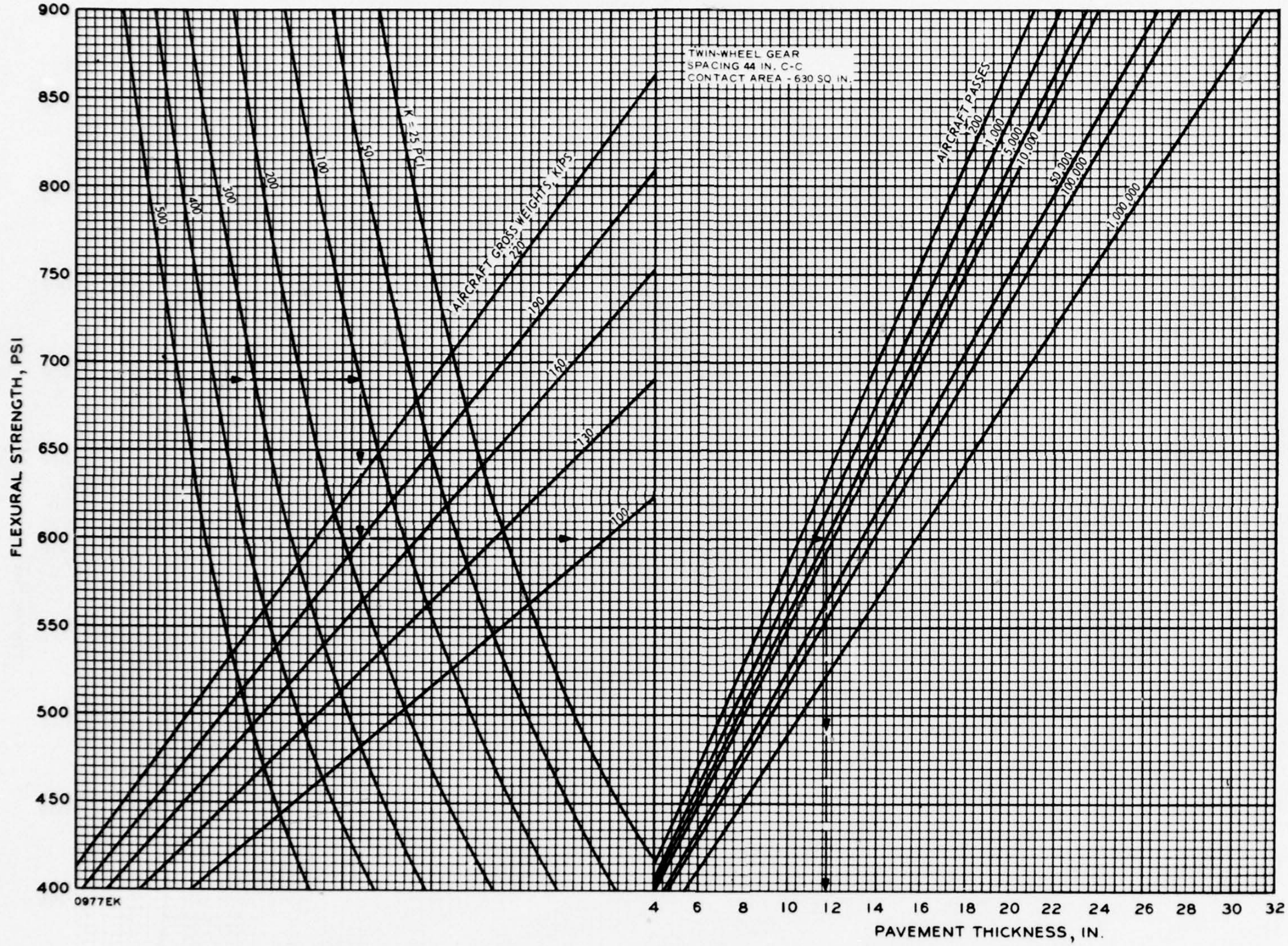

Figure 47. Rigid pavement design curves for army airfields, type B traffic areas (twin-wheel gear, contact area - 630 sq in.)

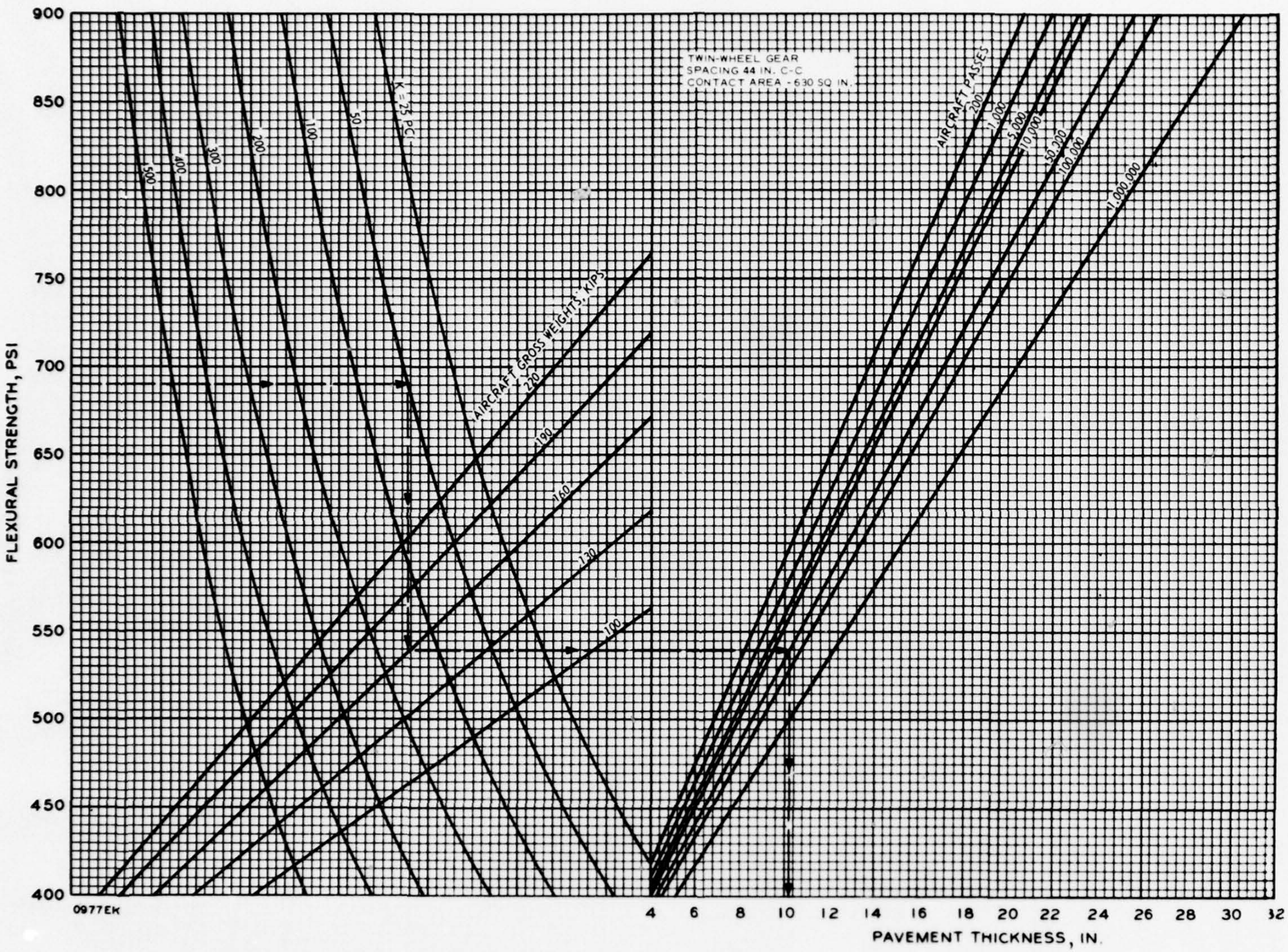

Figure 48. Rigid pavement design curves for army airfields, type C trafffic areas (twin-wheel gear, contact area - 630 sq in.)

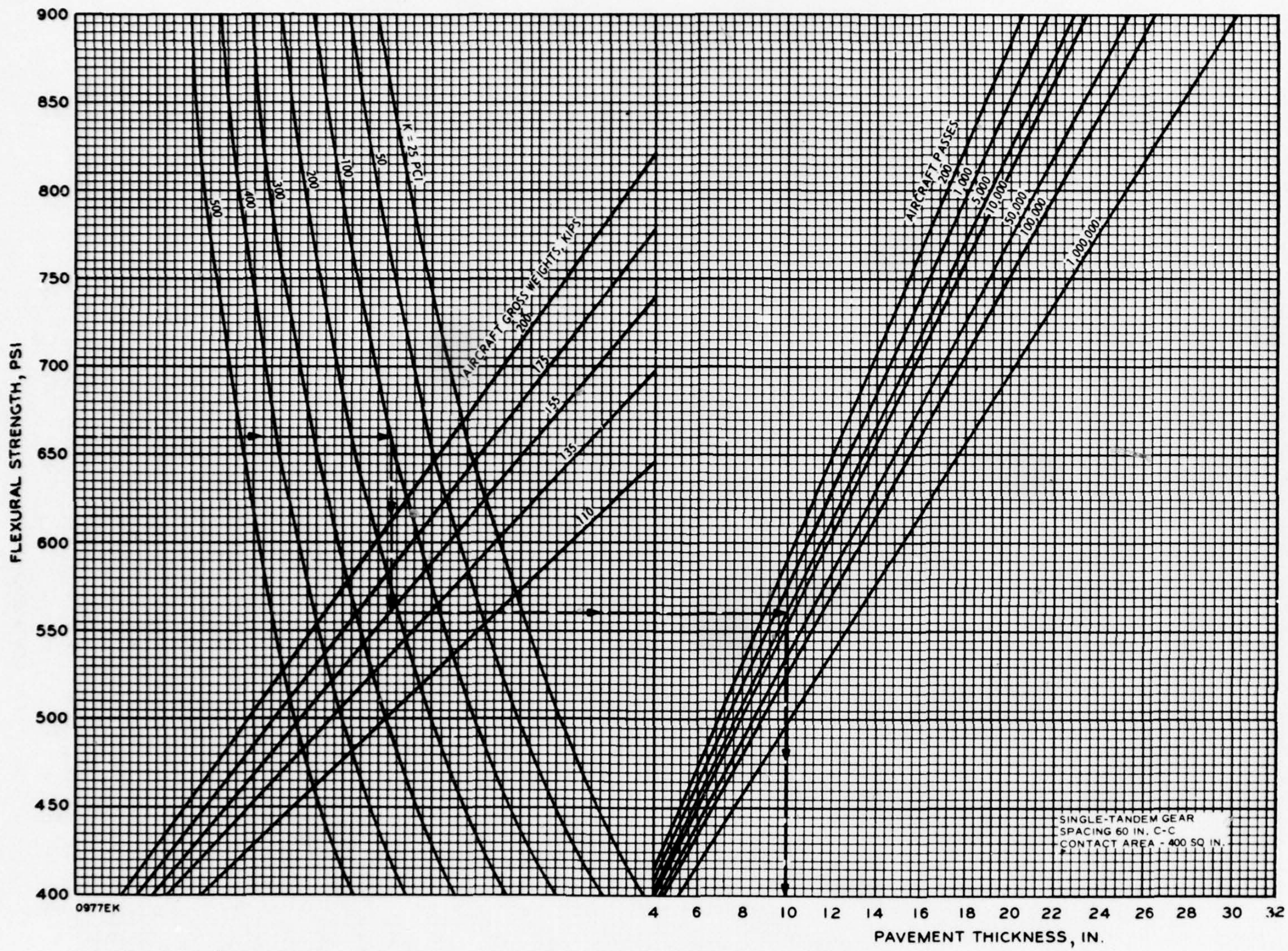

Figure 49. Rigid pavement design curves for army airfields, type B traffic areas (single-tandem gear, contact area - 400 sq in.)

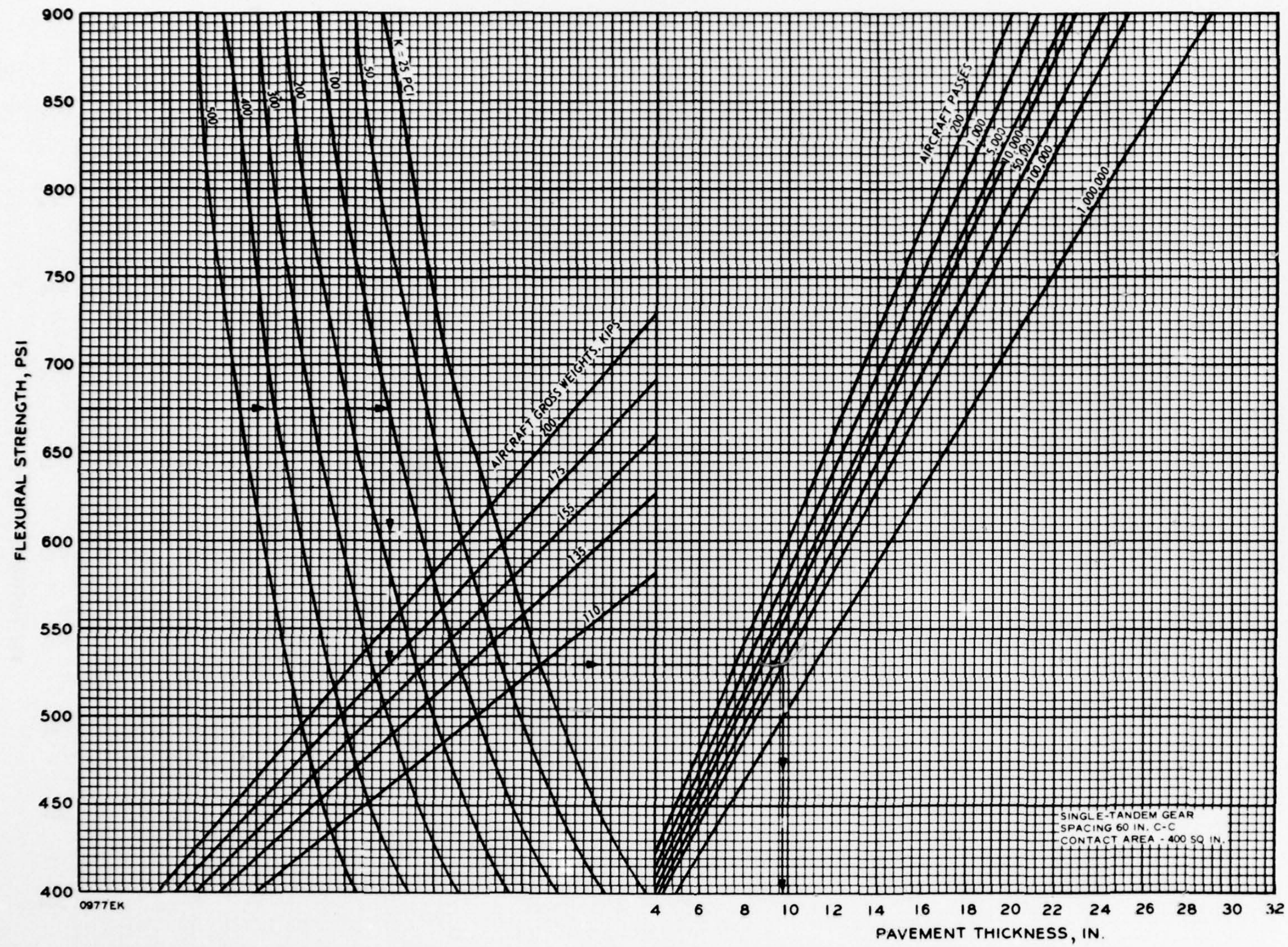

Figure 50. Rigid pavement design curves for army airfields, type C traffic areas (single-tandem gear, contact area - 400 sq in.)

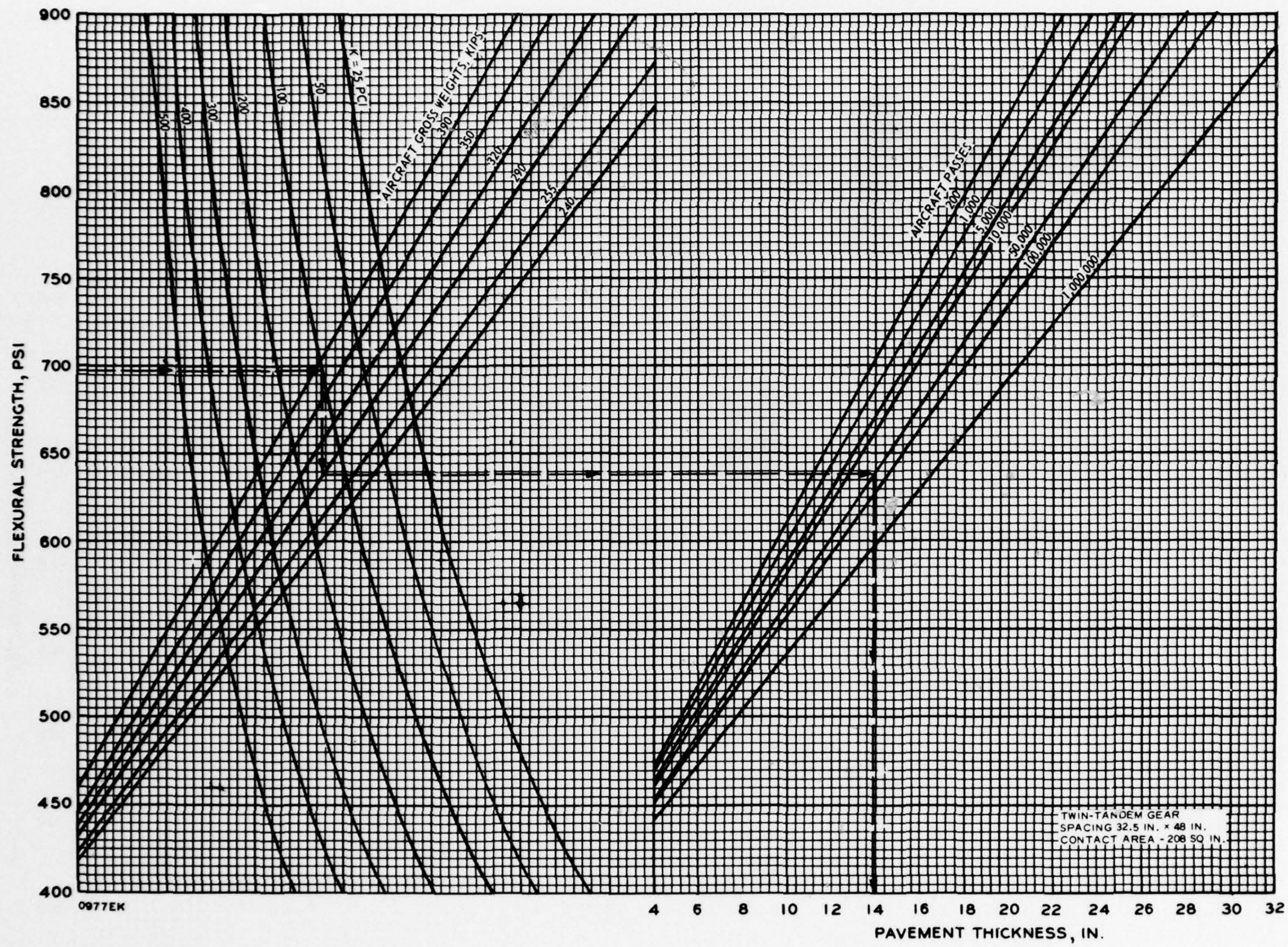

Figure 51. Rigid pavement design curves for army airfields, type B traffic areas (twin-tandem gear, contact area - 208 sq in.)

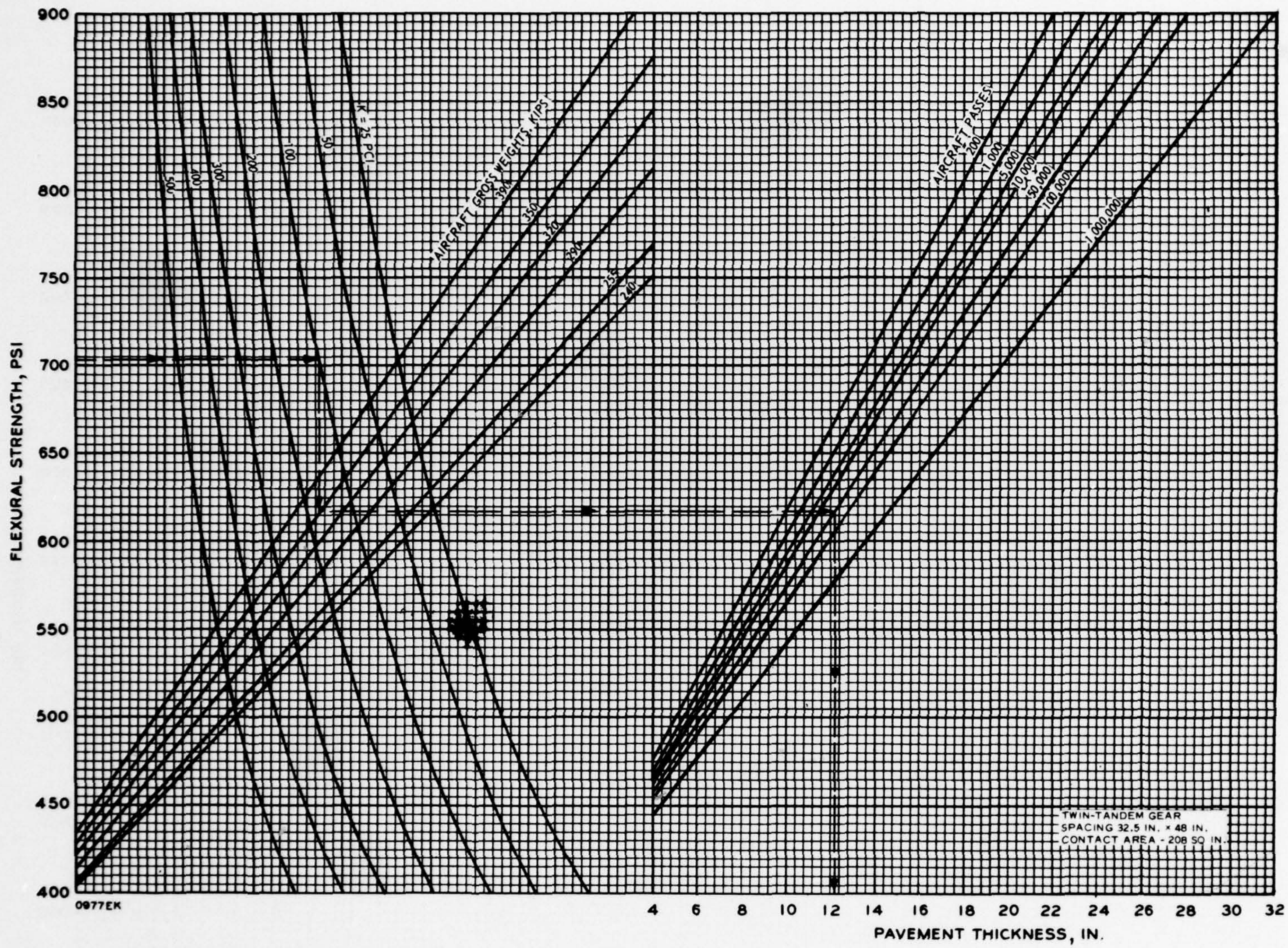

Figure 52. Rigid pavement design curves for army airfields, type C traffic areas (twin-tandem gear, contact area - 208 sq in.)

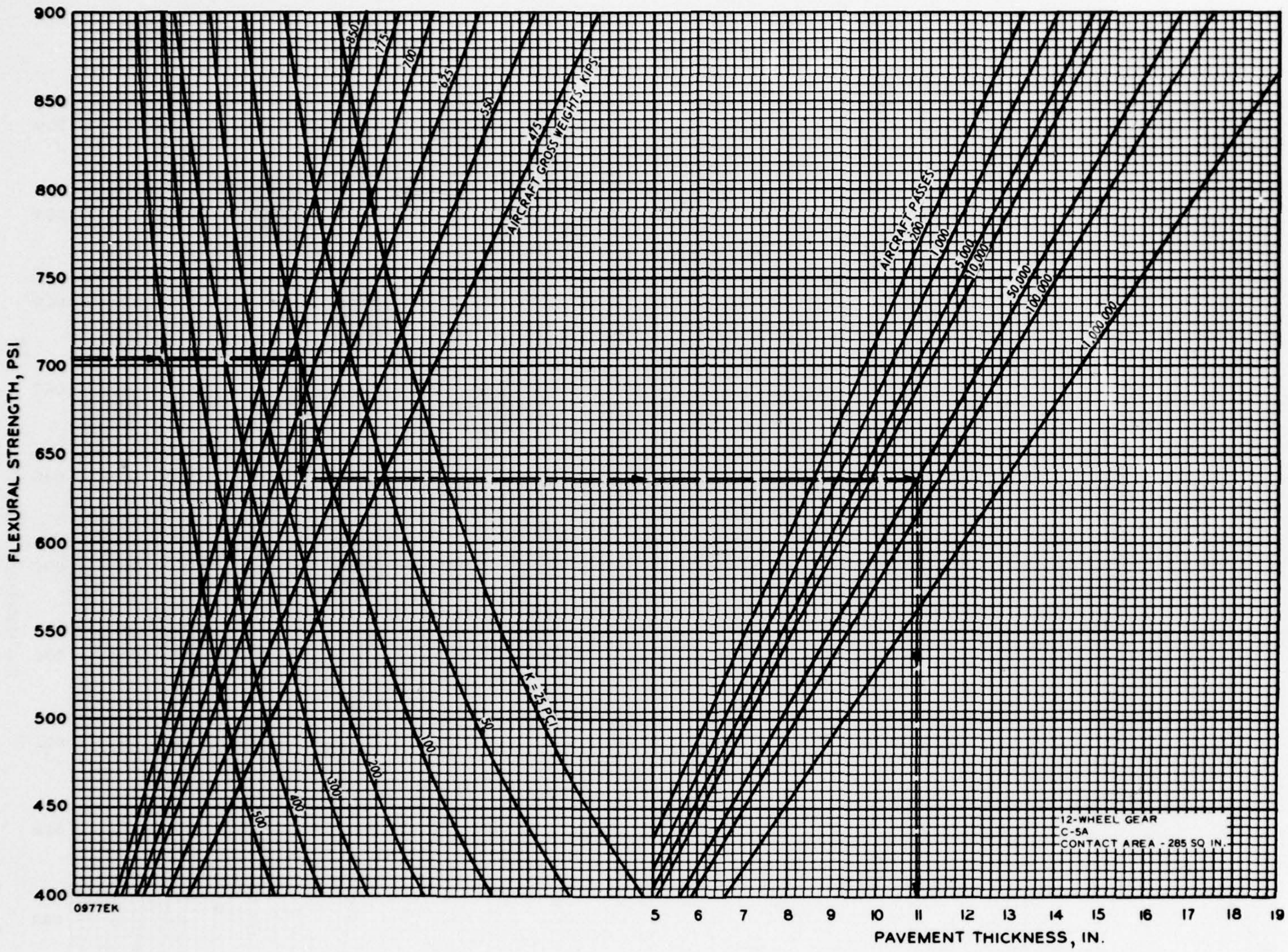

Figure 53. Rigid pavement design curves for army airfields, type B traffic areas (12-wheel gear, contact area - 285 sq in.)

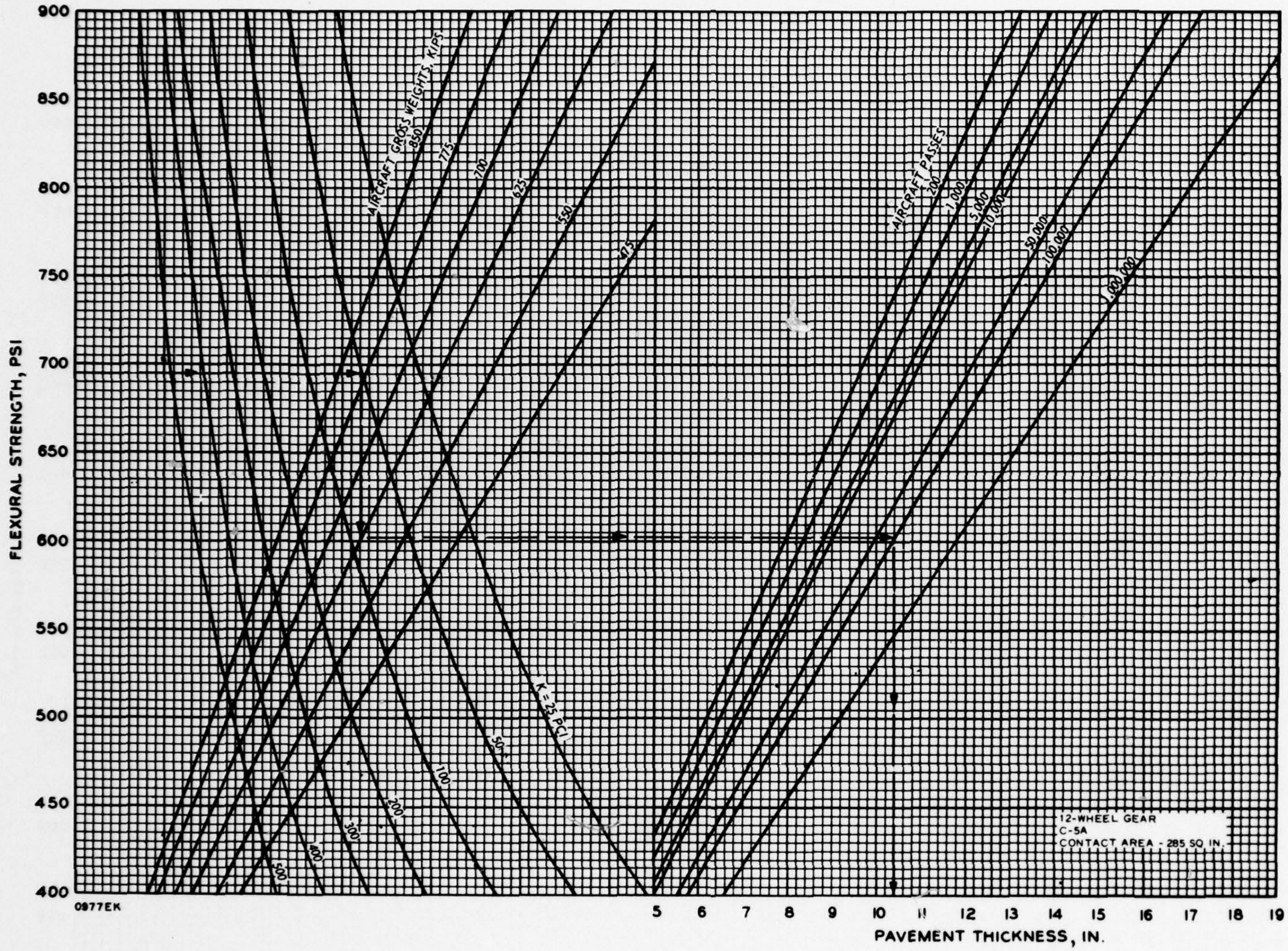

Figure 54. Rigid pavement design curves for army airfields, type C traffic areas (12-wheel gear, contact area - 285 sq in.)

APPENDIX A: EXAMPLE OF FLEXIBLE PAVEMENT EVALUATION AND OVERLAY COMPUTATION

Required Information and Test Data

A nondestructive pavement evaluation and overlay design is to be made on a section of runway for the following conditions:

Pavement section

	Material	Thickness, in.
Surface	Asphaltic concrete	6
Base	Cement-stabilized sand gravel	10
Subbase	Sand gravel	10

Test data

Pavement mean temperature = 90°F (adjustment factor = 1.2, Figure 6). DSM measurements:

Test No.	Location sta	Measured DSM	Adjusted (to 70°F) DSM
1	100+00	892	1070
2	101+00	967	1160
3	102+00	1208	1450
4	103+00	1200	1440
5	104+00	817	980
6	105+00	733	880
7	106+00	883	1060
8	107+00	983	1180
9	108+00	850	1020
10	109+00	750	900
11	110+00	1025	1230
12	111+00	858	1030
13	112+00	958	1150

Mean DSM = 1120

Mission requirements (design load)

C141 aircraft: contact area = 208 sq in.

gross load = 300,000 lb

10,000 passes

Evaluation of Existing Pavement

Determined load factor F_k

Convert 10,000 passes to coverages using pass per coverage ratio of 1.72; 10,000 passes ÷ 1.72 = 5814 coverages.

Enter Figure 9 with 5814 coverages for a dual-tandem aircraft (eight main gear wheels) and obtain $F_k = 0.0575$. Add 0.0002 to F_k because the contact is larger than 200 sq in. F_k for evaluation is $F_k = 0.0577$.

Compute the equivalent pavement section

Convert the existing pavement section to a required equivalent section made of 3-in. AC, 6-in. crushed stone base, and granular subbase. Appropriate equivalency factors are selected from Table 2, and all the existing pavement is first converted to total equivalent subbase. The total equivalent subbase T_s is then converted to the total equivalent pavement section T_T for evaluation.

Example of Equivalent Section

Existing Pavement	Equivalency Factor	Total Equivalent Subbase
6-in. asphaltic concrete	1.70	10.2
10-in. cement-stabilized sand gravel base	1.60	16.0
10-in. granular subbase	1.00	10.0
		$T_s = 36.2$

The total equivalent pavement thickness for evaluation purposes is then computed from the equation

$$
\begin{aligned}
T_T &= 3\text{ AC} + 6\text{ base} + (T_s - 13.5)\text{ subbase} \\
&= 9 + (T_s - 13.5) \\
&= T_s - 4.5 \\
&= 36.2 - 4.5 \\
&= 31.7\text{ in.}
\end{aligned}
$$

Note that the 13.5 in. used above is the result of converting the required 3-in. AC and 6-in. base to equivalent subbase.

If T_s is less than 13.5 in., then the equation to use for computing T_T is

$$T_T = 3 + \frac{T_s - 5.1}{1.40}$$

Select the percent
equivalent single-wheel load

From Figure 10, select the percent ESWL for the C141 and a depth of 31.7 in. percent ESWL = 60 percent.

Compute the allowable
gross aircraft load P_G

$$P_G = \frac{F_k(\mathrm{DSM})}{(\%\mathrm{ESWL})S} \times \frac{Nm}{Nc} \times 100$$

$$= \frac{0.0577(1120)}{60(0.90)} \times \frac{8}{4} \times 100$$

$$= 239.35 \text{ kips}$$

$$= 239{,}350 \text{ lb}$$

Pavement Overlay Thickness Design

Since the evaluated gross load was less than the mission requirements, a strengthening overlay is required.

Determine total
required pavement thickness

Compute the allowable gross single-wheel aircraft load P_{ASWL} for 24,000 passes from the formula

$$P_{ASWL} = 0.097\ (\mathrm{DSM})$$

$$= 0.097(1120)$$

$$= 108.64 \text{ kips}$$

Enter Figure 23 with the equivalent pavement thickness of 31.7 in., P_{ASWL} = 108.64 kips, and 24,000 passes to determine an effective subgrade CBR of 4.6. Then, enter Figure 35 with the CBR of 4.6, design load of 300,000 lb, and 10,000 passes to obtain a total required pavement thickness T_R of 38.

Compute overlay thickness

The overlay thickness, the difference in the total required thickness and the existing equivalent thickness divided by the equivalency factor for asphaltic concrete, is computed as follows:

$$\text{Overlay thickness} = \frac{38.0 - 31.7}{1.7} = \frac{6.3}{1.7} = 3.7 \text{ in.}$$

APPENDIX B: EXAMPLE OF RIGID PAVEMENT EVALUATION AND OVERLAY COMPUTATION

Required Information and Test Data

A nondestructive pavement evaluation and overlay design is to be made on a section of runway for the following conditions:

Pavement section

	Material	Thickness, in.
Surface	PCC	10
Base	Sand gravel	10

Test data

Test No.	Location Sta	DSM kips/in.	Deflection $\Delta 18$, in.	Measurements $\Delta 60$, in.	$\frac{\Delta 60}{\Delta 18}$	Radius of Relative Stiffness ℓ
1	40+00	1460	0.00447	0.00285	0.64	38
2	42+00	1450	0.00582	0.00381	0.66	41
3	44+00	1440	0.00583	0.00387	0.66	41
4	46+00	1510	0.00584	0.00438	0.75	52
5	48+00	1350	0.00451	0.00257	0.57	33
6	50+00	1470	0.00514	0.00323	0.63	38
7	52+00	1500	0.00423	0.00262	0.62	35
8	54+00	1710	0.00534	0.00331	0.62	35
9	56+00	1700	0.00410	0.00234	0.57	33
10	58+00	1590	0.00352	0.00237	0.67	41
11	60+00	1650	0.00544	0.00332	0.61	36

Mean values: DSM = 1530

$\ell = 38$

Mission requirements (design load)

C141 aircraft: contact area = 208 sq in.

gross load = 300,000 lb

10,000 passes

Evaluation of Existing Pavement

Determine load factor F_L

From Figure 14, for $\ell = 38$, $F_L = 7.1$

Determine traffic factor T_c

From Figure 19, for 10,000 passes, $T_c = 1.02$

Compute the allowable gross aircraft load P_G

$$P_G = 0.0189(DSM)(F_L)(T_c)$$
$$= 0.0189(1530(7.1)(1.02)$$
$$= 209.4 \text{ kips}$$

Pavement Overlay Thickness Design

Since the evaluated gross load was less than the mission requirements, a strengthening overlay is required. The overlay design may be for an AC overlay or for a PCC overlay.

Determine total required pavement thickness

Compute the subgrade modulus k from the equation

$$k = \frac{(24.4)^4 h^3}{\ell^4} = \frac{(24.4)^4 (10)^3}{(38)^4} = 169 \text{ pci}$$

Compute the allowable gross aircraft load (254 sq in., 24,000 passes) from the expression

$$P_G = 0.0189(DSM)(F_L)(T_c)$$
$$= 0.0189(1530)(2/0.9)(1.0)$$
$$= 64.3 \text{ kips}$$

In the case of a single-wheel aircraft for these conditions, the factor

F_L is simply two times the single-gear load divided by the factor of 0.9 for the nose gear, hence $F_L = 2/0.9$; the traffic factor T_c is 1.0 for these conditions.

Enter Figure 39 with the PCC thickness of 10 in., pass level of 24,000, allowable gross aircraft load of 64.3 kips, and subgrade modulus of $k = 169$, and determine the flexural strength R of the existing PCC. Then using this flexural strength ($R = 640$) and $k = 169$, enter Figure 51 and determine the total required PCC thickness of 12.8 in. for the design aircraft load and pass level.

Compute thickness
of flexible overlay

The required AC overlay is computed, as follows:

$$t = 2.5(Fh_d - C_b h)$$

$$= 2.5[(0.85)(12.8) - 0.75(10)]$$

$$= 8.5 \text{ in.}$$

where $F = 0.85$ from Figure 20 and $C_b = 0.75$.

Compute thickness of rigid overlay

The thickness of PCC overlay to be placed directly on the existing rigid pavement is computed in the following manner:

$$h_o = \sqrt[1.4]{(h_d)^{1.4} - C_r(h)^{1.4}}$$

$$= \sqrt[1.4]{(12.8)^{1.4} - 0.75(10)^{1.4}}$$

$$= 7.3 \text{ in.}$$

where $C_r = 0.75$.

APPENDIX C: NOTATION

A	Contact area of one tire, sq in.
AC	Asphaltic concrete
ASWL	Allowable single-wheel load
C_b	Condition factor of existing PCC slabs when designing flexible overlay
C_r	Condition factor of existing PCC slabs when designing PCC overlay
CBR	California Bearing Ratio
DSM	Dynamic stiffness modulus, kips per in.
E	Modulus of elasticity, psi
ESWL	Equivalent single-wheel load expressed as percent
F	Factor that projects the degree of cracking in PCC slabs
F_k	Load factor for flexible pavement
F_L	Load factor for rigid pavement
h	Thickness of existing PCC, in.
h_d	Required thickness of PCC for design load, in.
h_e	Equivalent thickness of PCC
h_o	Thickness of PCC overlay
k	Modulus of soil reaction, pci
ℓ	Radius of relative stiffness, in.
N_c	Number of controlling main-gear aircraft wheels
NDT	Nondestructive test
N_m	Number of main-gear aircraft wheels
P_{ASWL}	Allowable gross aircraft load with single-wheel gear
PCC	Portland cement concrete

P_G	Allowable gross aircraft load
S	Percent factor for load carried by nose gear
t	Thickness of AC overlay
T_c	Traffic factors for rigid pavement
T_s	Total equivalent subbase thickness, in.
T_R	Required total pavement thickness of flexible pavement
T_T	Total equivalent flexible pavement section thickness, in.
$\Delta 18$	Deflection 18 in. from load plate center
$\Delta 60$	Deflection 60 in. from load plate center
ν	Poisson's ratio

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Hall, Jim W

Nondestructive evaluation procedure for military airfields / by Jim W. Hall, Jr. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1978.

18, [65] p. : ill. ; 27 cm. (Miscellaneous paper - U. S. Army Engineer Waterways Experiment Station ; S-78-7)

Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under Project 4K07812AQ61.

References: p. 18.

1. Aircraft loads. 2. Airfield pavements. 3. Dynamic loads. 4. Military facilities. 5. Nondestructive tests. 6. Overlays (Pavements). 7. Pavement performance and evaluation. I. United States. Army. Corps of Engineers. II. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Miscellaneous paper ; S-78-7.

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